Evaluation of Water Quality Design Storms

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1 Introduction

Ongoing efforts to assess best management practices (BMPs) in Los Angeles County have repeatedly indicated a need to identify a water quality design storm for both planning and design purposes. Various Total Maximum Daily Loads (TMDLs) developed for Los Angeles County watersheds require comprehensive implementation plans to strategize specific BMPs to meet required pollutant load reductions. The selection and sizing of these BMPs are contingent on the hydrologic conditions requiring treatment. Identifying a water quality design storm can assist in:

- Determining BMP sizing requirements based on TMDL attainment
- Providing guidance for evaluation of BMP benefits
- Identifying thresholds for defining the most cost-effective practice for structural BMP implementation.

The Background section of this report summarizes a previous effort performed in the region to define a water quality design storm and presents some of the findings and key recommendations from that effort. The following section, The Proposed Modeling Approach, describes the Los Angeles County Flood Control District's regional Watershed Management Modeling System (WMMS), which serves as the enhanced platform for the recommended design storm development approach. It shows how the system's analytical components address and fulfill the key recommendations made in previous efforts. The section concludes with a comparison of the traditional use of a design storm to derive BMP treatment capacity versus the continuous simulation and optimization BMP design approach. The next section, Degree of Practice and Model Uncertainty, addresses the questions of risk and uncertainty and describes how these factors were considered in the overall analysis. The Model Results section presents a summary of model results, highlighting attainment cost as a function of both distributed and centralized BMP selection. Finally, The Water Quality Design Storm Section provides some options for water quality design storm consideration. It concludes with a summary discussion of the results and describes the implications of the proposed design storm options.

2 Background

The October 2007 technical report *Concept Development: Design Storm for Water Quality in the Los Angeles Region*, from the Southern California Coastal Water Research Project (SCCWRP), had two primary objectives:

1. Quantify the impact on water quality achieved through the management of design storms of varying size.
2. Compare the cost-effectiveness of different management strategies (BMPs) for achieving specific water quality targets with storms of varying size.

The study employed two methodologies for addressing these objectives. The first objective was addressed using a 30-year simulation of the Ballona Creek watershed implemented in *HSPF*. Percent total runoff volume and percent total copper load were examined as a function of increasing precipitation depth. Results showed that approximately 66 percent of the annual cumulative runoff volume occurred during precipitation events of 0.75 inch or less. Between 60 percent and 73 percent of the annual cumulative copper load also occurred during precipitation events of 0.75 inch or less. Further analysis confirmed that these relationships varied between wet and dry years.

The second objective was addressed by modeling three generalized BMPs in the Stormwater Management Model (*SWMM*). A 30-year runoff time series was generated using the *HSPF* model for a generic 10-acre, high-density residential site assuming 42 percent imperviousness. This time series was routed through three modeled BMPs: a vegetated swale, a flow-controlled swale, and a bioretention basin. The swale was modeled as a flow-through BMP with a flow splitter that bypasses flows exceeding a design flow rate. The flow-controlled swale design included an equalization basin for volume storage and routing to the swale. Bypass occurred only if the volume of the basin was exceeded.

Each BMP was evaluated for its treatment potential and cost-effectiveness in achieving the target reduction. BMP performance was evaluated by the fraction of runoff receiving treatment (percent capture) and the achievable effluent concentration measured as the fraction of discrete, 6-hour storm events exceeding the dissolved copper water quality benchmark.

Capital and maintenance costs for each of the three BMPs were estimated on the basis of design sizes that allow for 5 percent, 10 percent, and 20 percent exceedance of the dissolved copper standard. Capital costs were derived primarily from RSMeans cost data; maintenance costs were derived through literature sources. Both were adjusted for May 2007 using the Los Angeles consumer price index. The study concluded that the dominant component in the estimates was the cost for land for all three BMPs considered. Cost-effectiveness was measured as the total first-year costs normalized by the percent annual dissolved copper load reduction.

The SCCWRP study made some key assumptions and identified several technical challenges that arose during that modeling effort. The first set of challenges occurred in extrapolating results to other watersheds and in addressing other constituents. The study relied exclusively on rainfall records at the Los Angeles International Airport (LAX) gage located in the coastal plain region. Rainfall patterns across the County vary widely depending on several factors, most notably terrain.

BMPs were modeled using runoff generated from high-density residential land use. High-density residential was defined by assuming 42 percent impervious surfaces. Surface runoff flows and constituent loadings can vary widely across the range of potential land use categories. Factors such as slope also play an important role in the modeling of runoff and pollutant loads.

Copper (Cu) was the only constituent fully evaluated by the SCCWRP study. It is necessary to evaluate the behavior and response of other pollutants in the watershed in addition to copper. Fecal coliform, for example, is subject to different processes that affect its fate and transport.

The second major technical challenge involved confidence in the ability to accurately model BMP performance and copper. Total copper is most often used in modeling applications; however, the water quality standard used in the SCCWRP study was based on the dissolved copper concentration. This required making an assumption regarding the ratio of dissolved copper to total copper based on observations of hardness in Ballona Creek. The modeling of BMP performance also relied on a constant total copper effluent concentration based on literature values.

Three recommendations arose out of the technical challenges identified during the SCCWRP study:

1. Address extrapolation limitations by modeling additional constituents, land use types, and precipitation patterns.
    a. Incorporate rain gages that adequately reflect the varying rainfall patterns within the county.
    b. Model a representative distribution of land use categories to explore rainfall-water quality relationships beyond high-density residential.
    c. Evaluate rainfall-water quality relationships and BMP effectiveness at achieving water quality targets for a range of constituents.

2. Improve estimates of variance with regard to constituent loading, runoff concentrations, and modeling of BMP performance. This can be done by using techniques such as Monte Carlo simulation is a possible solution to account for variability.

3. Consider how water quality design storm standards should be implemented across an entire watershed. This includes opportunities and constraints of setting standards related to new development, redevelopment, and retrofit applications.

3 The Proposed Modeling Approach

The recently developed Los Angeles County WMMS modeling approach is a well-suited platform for evaluating water quality design storms. This section describes (1) the increased model resolution in terms of land cover, subwatershed delineation, and meteorological data; (2) an intuitive organizational method for classifying subwatershed and management opportunities; and (3) a description of how the various components have been integrated to evaluate optimal management strategies for sizing and placing BMPs at the watershed scale.

3.1 Increased Model Resolution

The updated regionalized watershed model for Los Angeles County includes specific changes that have been implemented to create a truly regionalized modeling approach that takes advantage of the strengths of previous modeling efforts, addresses identified weaknesses, and builds on the collective efforts and advances of the past few years. Tetra Tech performed a detailed evaluation of all the previous modeling efforts to evaluate and characterize similarities and differences. The following recommended upgrades were then applied:

- Refined land use representation to account for potential differences in soil hydrologic group and slope. The unique combination of land use, soil type, and slope represents a Hydrology Response Unit (HRU) for watershed modeling. The HRU approach simplifies the selection of model parameters and provides a clear physical basis for parameter assignment.
- Identified watershed-based “management categories” for planning BMP activities. While HRUs represent the hydrologic response for individual land features, management categories describe the physiographic features and impervious configuration of a subwatershed. Management categories are assigned within hydrologic boundaries (subwatersheds) because the associated factors that govern the selection and placement of structural BMPs within the subwatershed are hydrologic. These factors include (1) total impervious area, (2) impervious density (dispersed or concentrated), (3) average slope of urban areas within the subwatershed (less than or greater than 10 percent) and (4) average road density (high or low).
- Developed a standard methodology for watershed sizing. For subwatershed sizing, Tetra Tech developed an approach that is based on the fixed criterion of total impervious area within a subwatershed. For example, given a fixed upper impervious cover limit, areas with relatively concentrated impervious area have smaller subwatersheds, whereas areas with more dispersed impervious area have larger subwatersheds. Another advantage of this approach is that because impervious area is usually the main river for runoff volume, subwatersheds having relatively equal impervious area tend to generate comparable total flows and pollutant loads.
- Weather data inputs have been refined with the most recent and detailed weather data available.

3.1.1 Hydrologic Response Units

In a watershed model, land unit representation should be sensitive to the features of the landscape that most affect hydrology and pollutant transport. In urban areas, it is important to estimate the division of land use into pervious and impervious components; in rural areas, vegetative cover is more important. Agricultural practices and crops (or crop rotations) should be well represented when present, although this component is less a factor in Los Angeles County (where only about 1 percent of the total watersheds’ area is agricultural) than in other areas. Depending on the goals of the model, if soil hydrologic groups are not homogeneous in a watershed, it might be important to further divide pervious land cover by soil hydrologic group so that infiltration processes are better represented. Slope might also be an important factor, especially if steep slopes are prevalent; high slopes influence runoff and moisture-storage processes. The combination of land use, soil hydrologic group, and slope was used to define the HRUs. This section details the HRU development processes for the Los Angeles County WMMS.

For this analysis, the Los Angeles County 2005 Land Use layer was originally processed and summarized to characterize land use for watersheds within the County's boundaries (LACDPW 2008a). The analysis was later refined to include spatial boundaries from the County's Parcel layer. Although the Parcel layer contained a high degree of spatial resolution for privately owned parcels, it was not as useful for representing public parcels (LACDPW 2008b). Therefore, the final land use layer represents a hybrid construction that uses the best available information from a variety of spatial data sources to create composite land use and imperviousness maps.

The Parcel layer included runoff factors for selected parcels, which were used as a surrogate indicator of impervious cover. When no data were available, imperviousness values from the County's Land Use layer were applied. The National Land Cover Data (NLCD 2001 Impervious Surface) from the U.S. Geological Survey (USGS) website was used to estimate the percent imperviousness for watersheds outside the Los Angeles County boundary (USGS 2008). The Los Angeles County subwatershed layer was used as the spatial extent to derive the average percent imperviousness of each land use category given in the 2005 Land Use layer. A zonal statistics analysis of the final composite imperviousness layer was performed by intersecting it with the composite land use layer and computing an area-weighted percent imperviousness for screening-level evaluation. The final composite land use layer was grouped into 12 major categories: agriculture, commercial, high-density single-family residential, industrial, institutional, low-density single-family residential, multifamily residential, open recreational, secondary roads, transportation, vacant land, and water.

Within the urban areas, impervious land areas for each land use type are independently represented as their own HRU categories. For watershed modeling using LSPC, impervious land uses should be represented as directly connected impervious areas; therefore, it is important to resolve how impervious areas are handled in the model. Once total impervious area, or Mapped Impervious Area (MIA), is determined for land use polygons, it is necessary to estimate the Effective Impervious Area (EIA), which is the portion of MIA directly connected to the drainage collection system. Impervious area that is not connected to the drainage network has the opportunity to flow onto pervious surfaces, infiltrate, and become part of pervious surface overland flow; such disconnected impervious area is often represented as pervious land surfaces. In practice, runoff from disconnected impervious surfaces often overwhelms the infiltration capacity of adjacent pervious surfaces, and the runoff might reconnect to nearby impervious surfaces. Finding the right balance between MIA and EIA can be an important part of hydrology calibration, especially in urban areas. Because it is expected that for most of the heavily urbanized areas within the Los Angeles County boundary MIA will be equal to EIA, this was assumed in the development of the HRU layer.

Pervious urban land areas are typically a combination of managed pervious land (e.g., irrigated lawns, other urban grass) and natural cover (treed areas or bare ground). These types of managed pervious land are common to all urban land use categories, although the relative distribution within each category typically varies. For these areas, two HRU categories, "Urban Grass (irrigated)" and "Urban Grass (non-irrigated)" were selected for Los Angeles County.

The "Vacant" land category represents 59 percent of the watershed area. It is recognized that physical features of vacant land are not homogeneous throughout the watershed; that is, not all vacant land responds to weather in the same way. For this reason, there is a need to further refine this land use category to better represent the physical variability and variations in hydrologic response to weather. The combination of land use, soils, and slope influence provides a sound physical basis for refining and differentiating the representation of vacant land. The details of this refinement are described in the following section.

For this analysis, the State Soil Geographic (STATSGO) and Soil Survey Geographic (SSURGO) data were processed and summarized to characterize hydrologic soil groups (HSGs) in the County's regional watersheds (NRCS 2008). The Los Angeles County subwatershed boundary was used as the spatial extent to derive the percent distribution of each HSG within each land use category given in the 2005 Land Use layer. In general, a cursory analysis showed that developed areas tend to be concentrated in areas with relatively poorly draining hydrologic soil group D soils. Nearly half of the vacant land is composed of D soils, but the other half is almost evenly divided between B and C soils.

In terms of slope, the developed areas are almost exclusively in areas having less than a 10 percent slope, while the more highly sloped areas are almost exclusively vacant. The low-density single-family residential and open recreational areas have mixed slope.

In the Los Angeles County climate, irrigation of lawns and agricultural areas is necessary to sustain viable plants. To improve the simulation of selected low-flow hydrology components, this additional supply of water must be considered. Because application rates across the watershed are rarely known, estimates of irrigation are required. In California, these estimates are typically based on the reference evapotranspiration rates measured at a nearby California Irrigation Management Information System (CIMIS) station, along with daily rainfall data and crop or grass coefficients specific to each land use. This method typically results in simulation of some baseflows during the summer. While the objective of the watershed modeling is focused on stormwater representation, accounting for irrigation and its effect on groundwater and baseflow will help to provide at least an estimate for load contributions associated with urban irrigation flows during the summer months. That is why irrigated urban pervious surfaces are categorized as an independent HRU.

For the existing Calleguas Creek and Santa Clara River *HSPF* model, Aqua Terra (2005, 2008) developed a detailed approach for simulating irrigation applications. It consists of two components: (1) calculation of potential irrigation demand based on cropping data, cover coefficients, reference evapotranspiration (ET), and irrigation efficiency and (2) calculation of daily irrigation applications after accounting for rainfall contributions to crop and lawn demands. The percent irrigation values for Los Angeles watersheds are derived from these sources. They are 50 percent for low-density residential; 70 percent for medium-density residential; 80 percent for high-density residential; and 85 percent for the commercial, industrial, or transportation land use category.

The screening-level analysis of land use, slope, and soil type indicated a few key spatial trends:

- The developed areas are concentrated in areas that have relatively poorly draining group D soils.
- Nearly half of the vacant land is composed of D soils, but the other half is almost evenly divided between B and C soils.
- The developed areas are almost exclusively in areas that have slopes of less than 10 percent.
- The highly sloped areas (greater than 10 percent slope) are almost exclusively vacant.

The methodology for developing HRUs addressed two groups—urban and non-urban areas—separately. For urban areas, soil layer was not used because the screening-level analysis indicated that most of the urban areas have type D soils. The steps for developing the HRUs are summarized below:

1. For urban areas
    a. Use Los Angeles County subwatershed polygons (2,655 in all) for spatial extent of analysis.
    b. Intersect the composite land use layer and composite percent imperviousness layer to derive the area-weighted percent imperviousness for each land use polygon.
    c. Using the USGS elevation (10-meter resolution) layer, derive a percent slope layer at the same resolution.
    d. Create a slope class layer with two categories: (1) 0 to 10 percent slope and (2) greater than 10 percent slope.

e. Integrate spatial data for impervious areas.
   i. Perform union of urban land uses and subwatershed polygons.
   ii. Overlay slope class layer with urban land use and subwatershed union polygon and summarize the distribution of slope class in urban land use areas by subwatershed.
   iii. Overlay composite imperviousness layer with urban land use and subwatershed union polygons and summarize impervious area by land use and subwatershed.

f. For pervious land use areas (e.g., pervious residential, commercial, institutional), apply land-use-specific weighting factors to reclassify the pervious land use areas into the two functional urban pervious HRUs—Urban grass (irrigated) and Urban (non-irrigated).

2. For non-urban areas
   a. Use SSURGO and STATSGO layers to derive HSG for the study area.
   b. Perform union of slope class layer and soil hydrologic soil group layer.
   c. Perform union of non-urban land uses from composite land use layer with subwatershed polygons.
   d. Overlay step 2c union with step 2b union, and summarize relative distribution of soil and slope combinations in non-urban land by subwatershed.

Soil type and slope are often strongly correlated. Given the level of detail, even with two categories, in a GIS file based on a union of land use/land cover, soil hydrologic group and slope can create a very large number of polygons and become unmanageable. One observation is that development is almost entirely confined to areas with low slope (less than 10 percent); therefore, low/high slope designation was used exclusively in non-urban areas. To further reduce the complexity of the resulting HRU product, while providing the benefit of added resolution where most needed, the application of soil type and slope was initially confined to only the vacant land use and agricultural categories.

The process of developing the HRUs proved that some of the resulting combinations were very small or negligible in terms of total area, and hence they were eliminated from the HRU list. Table 1 lists the HRUs that resulted from this analysis, and Table 2 summarizes the land use area for each HRU category in the County's regional watersheds. Figure 1 shows the spatial distribution of preliminary HRUs in Los Angeles County.

Table 1. Preliminary HRUs for Los Angeles County regional watersheds

<table>
<tr><th>HRU</th><th>Land use categories</th><th>Impervious/pervious</th><th>Slope</th><th>Soil group</th></tr>
<tr><td>Urban grass (irrigated)</td><td rowspan="2">Includes pervious portions of HD single-family residential, LD single-family residential, multifamily residential, commercial, institutional, industrial, transportation, and open recreational</td><td>Pervious portion only</td><td>0%–10%</td><td>D</td></tr>
<tr><td>Urban grass (non-irrigated)</td><td>Pervious portion only</td><td>0%–10%</td><td>D</td></tr>
<tr><td>HD single-family residential</td><td>HD single-family residential</td><td>Impervious portion only</td><td>0%–10%</td><td>n/a</td></tr>
<tr><td>LD single-family residential moderate slope</td><td rowspan="2">LD single-family residential and open recreational</td><td rowspan="2">Impervious portion only</td><td>0%–10%</td><td rowspan="2">n/a</td></tr>
<tr><td>LD single-family residential steep slope</td><td>> 10%</td></tr>
<tr><td>Multifamily residential</td><td>Multifamily residential</td><td>Impervious portion only</td><td>0%–10%</td><td>n/a</td></tr>
<tr><td>Commercial</td><td>Commercial</td><td>Impervious portion only</td><td>0%–10%</td><td>n/a</td></tr>
<tr><td>Institutional</td><td>Institutional</td><td>Impervious portion only</td><td>0%–10%</td><td>n/a</td></tr>
<tr><td>Industrial</td><td>Industrial</td><td>Impervious portion only</td><td>0%–10%</td><td>n/a</td></tr>
<tr><td>Transportation</td><td>Transportation</td><td>Impervious portion only</td><td>0%–10%</td><td>n/a</td></tr>
</table>

HRU	Land use categories	Impervious/pervious	Slope	Soil group
Secondary roads	Secondary roads	Impervious portion only	0%–10%	n/a
Agriculture moderate slope B	Agriculture	Pervious	0%–10%	B
Agriculture moderate slope D			0%–10%	D
Vacant steep slope A	Vacant	Pervious	> 10%	A
Vacant moderate slope B			0%–10%	B
Vacant steep slope B			> 10%	B
Vacant steep slope C			> 10%	C
Vacant moderate slope D			0%–10%	D
Vacant steep slope D			> 10%	D
Water	Water	n/a	n/a	n/a

Table 2. HRU distribution in Los Angeles County regional watersheds

HRU	Impervious/ pervious	HRU area (acre)	Percent of total HRU area
Urban grass (irrigated)	Pervious	300,983	13
Urban grass (non-irrigated)	Pervious	101,132	4
HD single-family residential	Impervious	254,170	11
LD single-family residential moderate slope	Impervious	43,686	2
LD single-family residential steep slope	Impervious	37,763	2
Multifamily residential	Impervious	89,712	4
Commercial	Impervious	68,924	3
Institutional	Impervious	44,543	2
Industrial	Impervious	93,368	4
Transportation	Impervious	31,794	1
Secondary roads	Impervious	145,456	6
Agriculture moderate slope B	Pervious	5,927	0
Agriculture moderate slope D	Pervious	14,477	1
Vacant moderate slope B	Pervious	48,677	2
Vacant moderate slope D	Pervious	41,924	2
Vacant steep slope A	Pervious	23,599	1
Vacant steep slope B	Pervious	270,256	11
Vacant steep slope C	Pervious	268,431	11
Vacant steep slope D	Pervious	497,386	21
Water	—	13,128	1

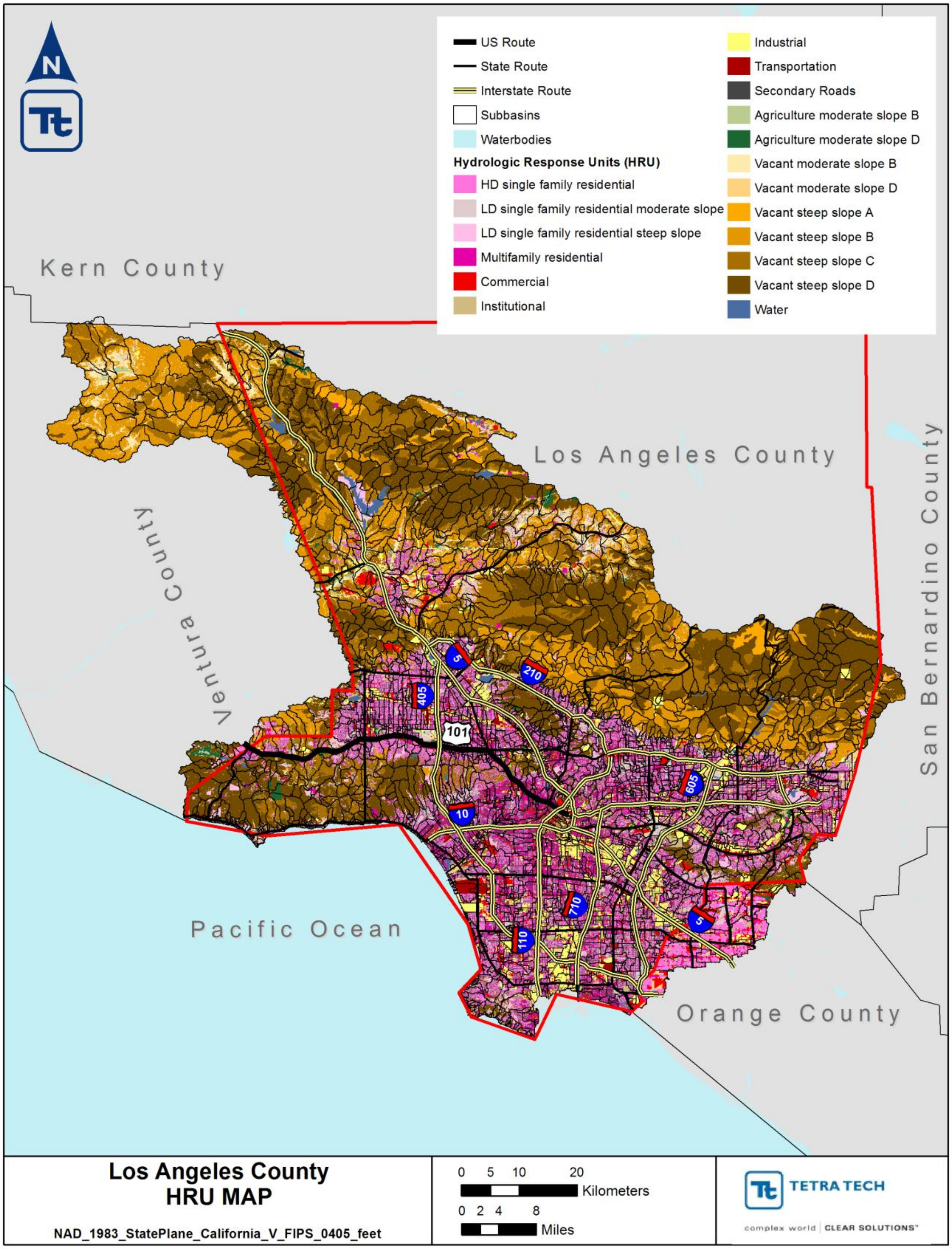

Figure 1. Hydrologic Response Unit representation in Los Angeles County regional watersheds.

3.1.2 Meteorological Data

Meteorological data are a critical component of the watershed model. Models require appropriate representation of precipitation and potential evapotranspiration. In general, hourly precipitation (or finer resolution) data are recommended for nonpoint source modeling and therefore are preferred. Rainfall-runoff processes for each subwatershed were driven by precipitation data from the most representative station. These data provide necessary input to LSPC algorithms for hydrologic and water quality representation.

Rainfall data from multiple sources were available at several locations in and around the Los Angeles County region (Figure 2). Four primary data sources of locally observed weather data were evaluated and processed for modeling: (1) the National Climatic Data Center (NCDC) hourly precipitation (21 gages), (2) the NCDC Summary of Day precipitation stations (48 total, of which 36 gages were selected based on screening-level quality and quantity assessment), (3) the Los Angeles County Department of Public Works (LACDPW) daily rainfall gages (9 gages), and (4) the Los Angeles County Flood Control District (LACFCD) daily rainfall gages (155 gages). There were some additional privately owned gages for which data were provided by the County. Finally, data from another set of recent 5-minute-interval rainfall gages (most beginning around the year 2000) maintained by the LACDPW were processed and archived. Of the 64 five-minute stations, 62 stations represent locations that are also among the daily LACFCD and LACDPW gage locations. Altogether, there were 512 unique rainfall datasets reported at daily, hourly, and 5-minute intervals at 448 unique locations. Data quality and quantity were evaluated at each of these locations, resulting in the selection of 148 datasets. Figure 3 shows data quality (shown as percent coverage of precipitation duration) for the 148 selected precipitation gages, summarized for water years 1997–2006.

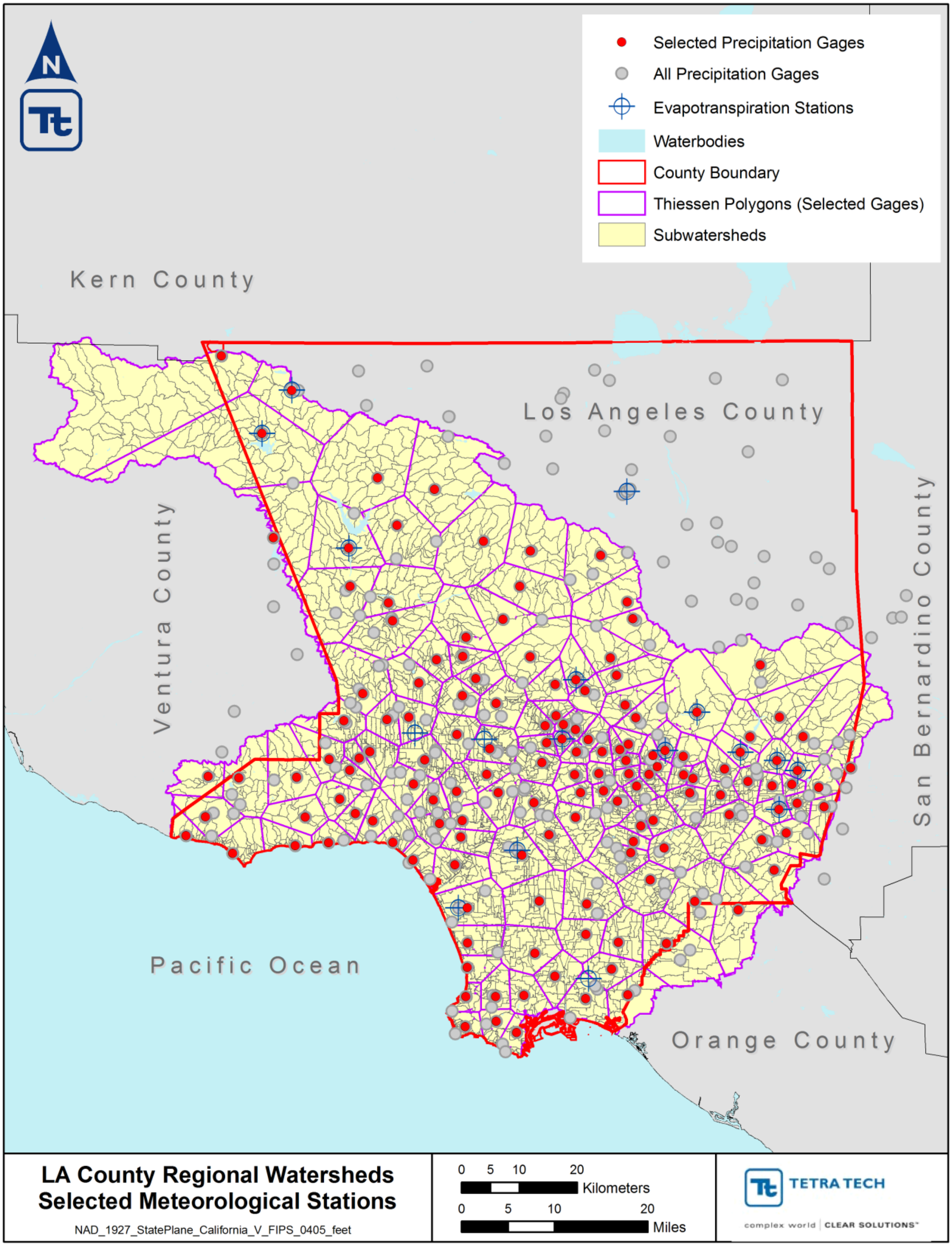

Figure 2. Location of measured precipitation gages for the Los Angeles County regional watersheds.

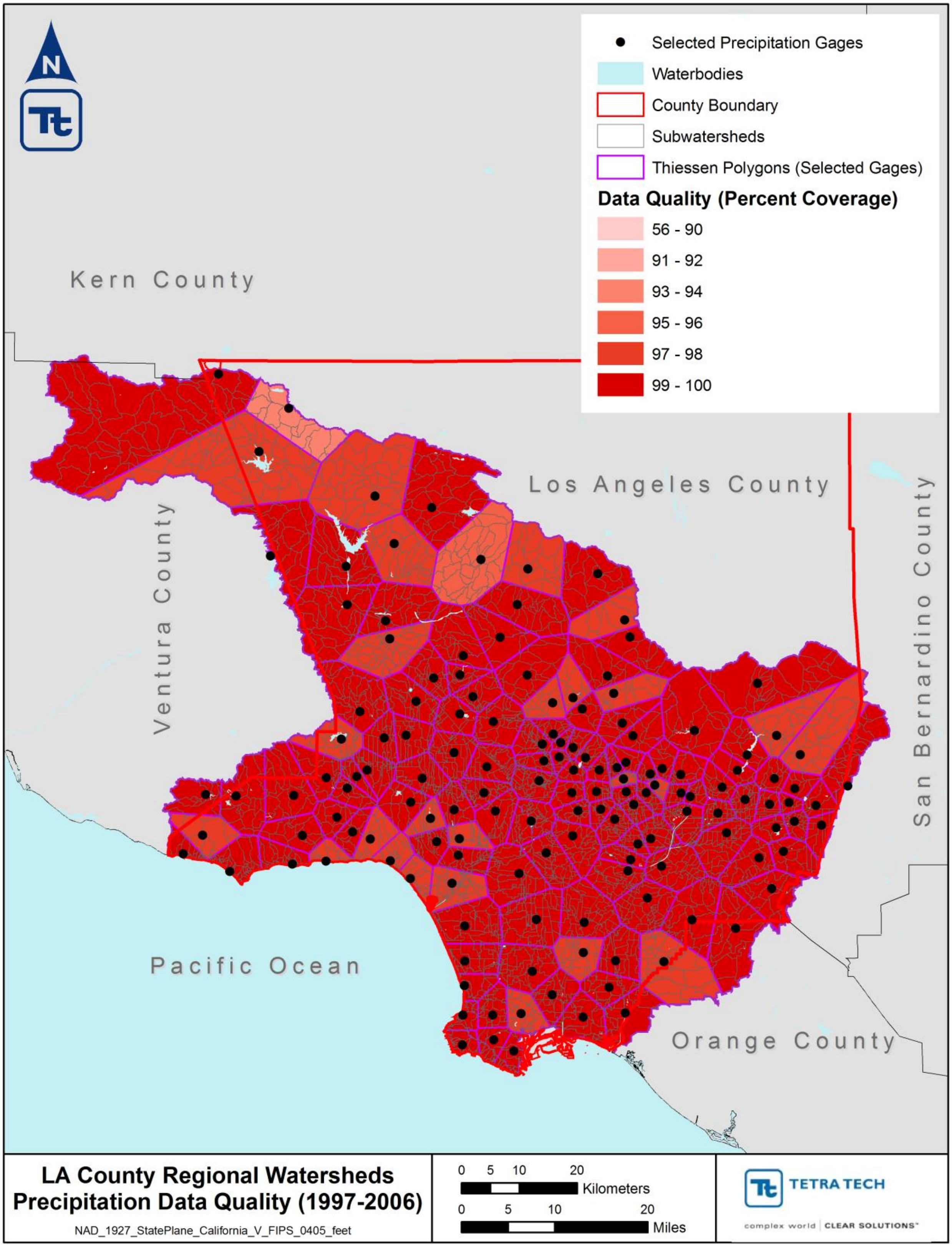

Figure 3. Data quality of selected precipitation gages summarized for 1997–2006.

Precipitation and evapotranspiration data were assigned to the subwatersheds using a Thiessen polygon methodology. Each subwatershed needs one precipitation and one evapotranspiration time series for LSPC. There are 148 unique rainfall locations. In an effort to manage the number of unique combinations of evapotranspiration and precipitation, evapotranspiration data were first assigned to a precipitation Thiessen polygon according to the highest percentage of intersecting evaporation and precipitation Thiessen polygons. Therefore, even after associating evapotranspiration, the number of unique weather combinations remains at 148. Figure 4 and Figure 5 shows annual average precipitation and evapotranspiration, respectively, throughout the Los Angeles County regional watersheds area, as well as station assignments by precipitation Thiessen polygon.

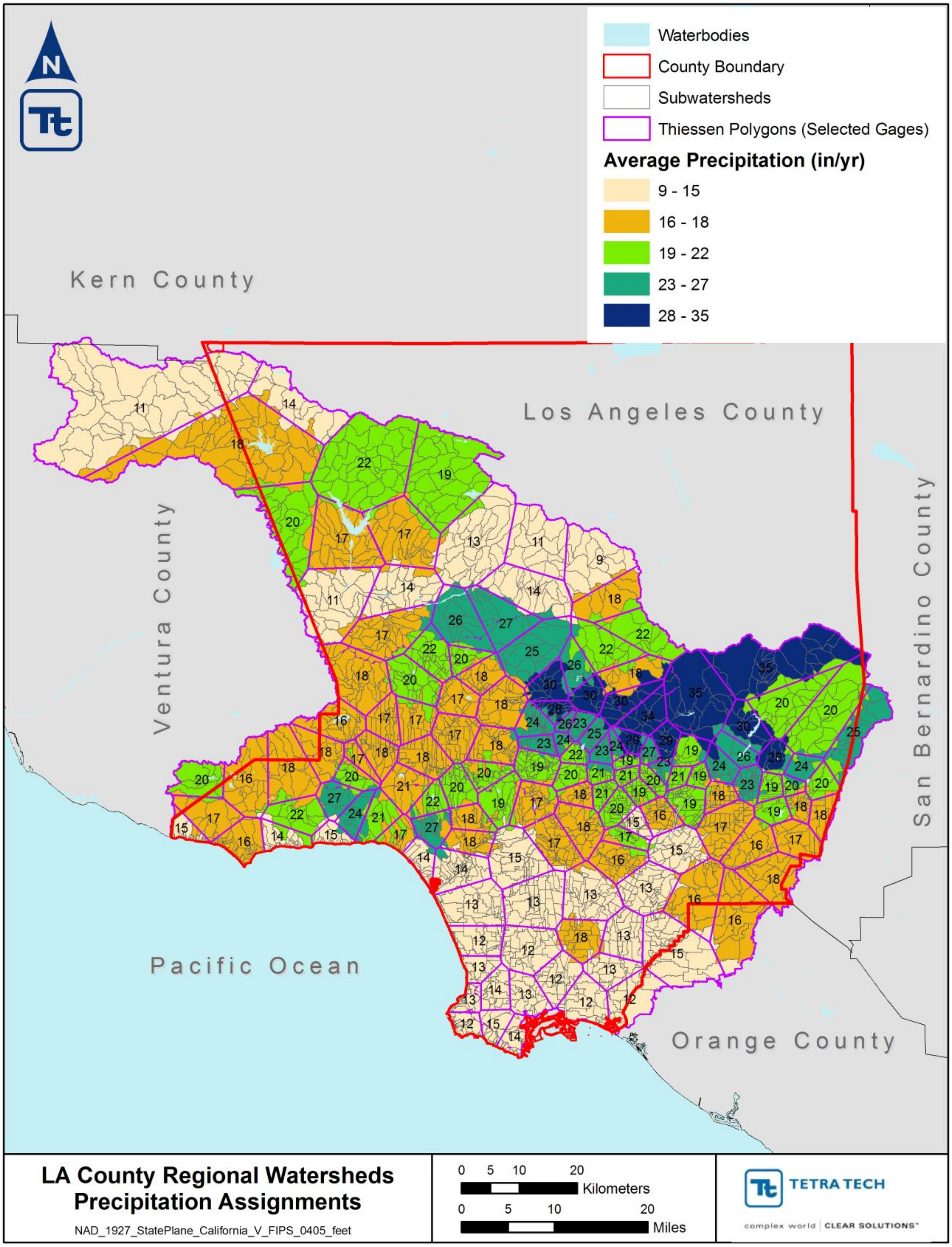

Figure 4. Average annual precipitation (1987–2006) by subwatershed for assigned modeling subwatersheds.

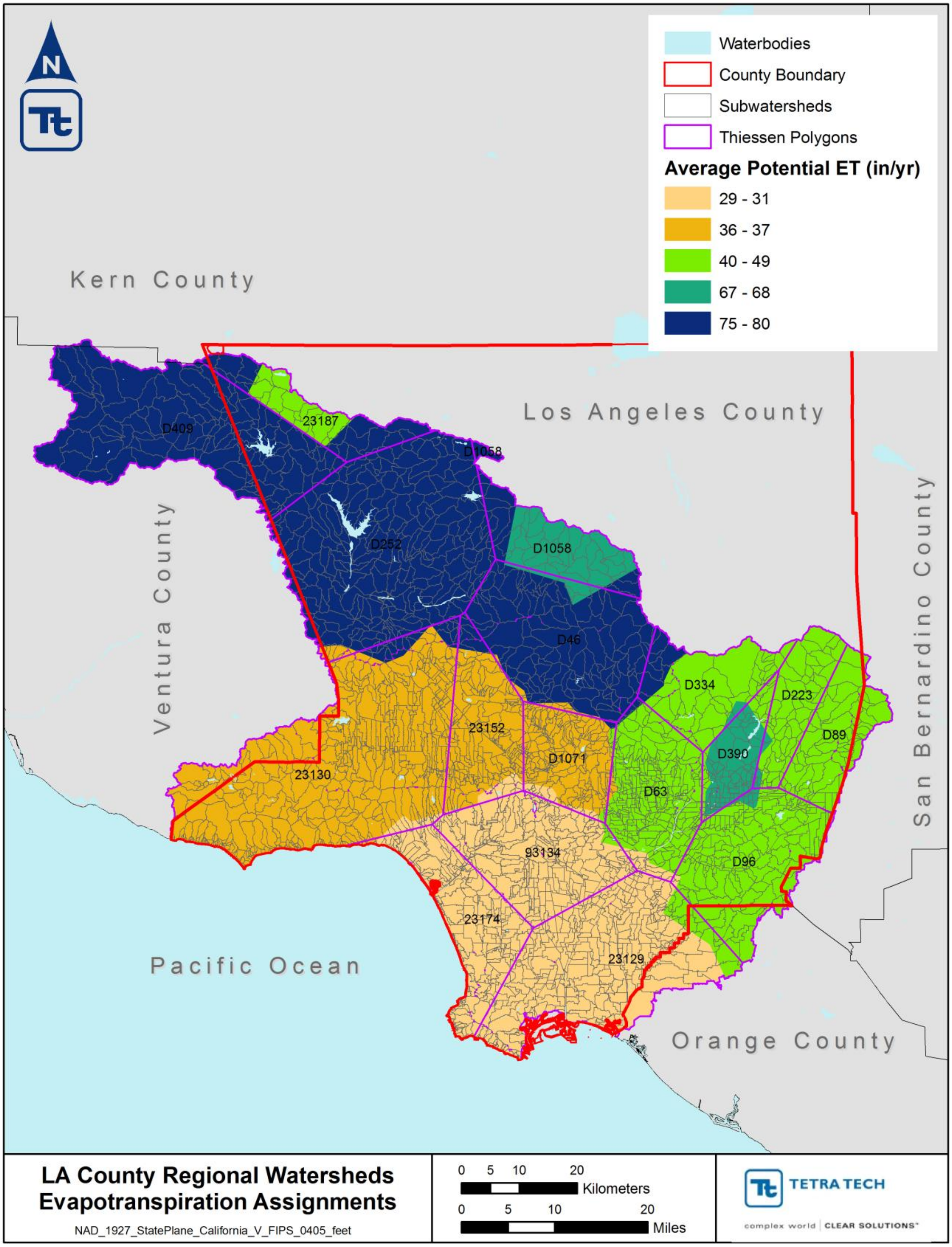

Figure 5. Average annual potential evapotranspiration (1987–2006) for assigned modeling subwatersheds.

3.1.3 Modeled Pollutants

The pollutants of concern modeled in the Los Angeles County WMMS are total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), copper (Cu), lead (Pb), zinc (Zn), and fecal coliform bacteria.

3.2 Management Categories and Levels

Management Categories and Management Levels are concepts developed to assist with organizing the watershed into subwatersheds with similar characteristics that most influence the type and degree of management that can be done throughout the Los Angeles County regional watersheds. Dividing the study area into smaller, manageable groups of subwatersheds and levels of management divides the challenge of deriving regional guidance and recommendations into smaller units, which are easier to study and understand. As illustrated in Figure 6, Management Categories are spatial classifications assigned on a subwatershed basis, while Management Levels represent different intensities of BMP implementation within a given Management Category subwatershed.

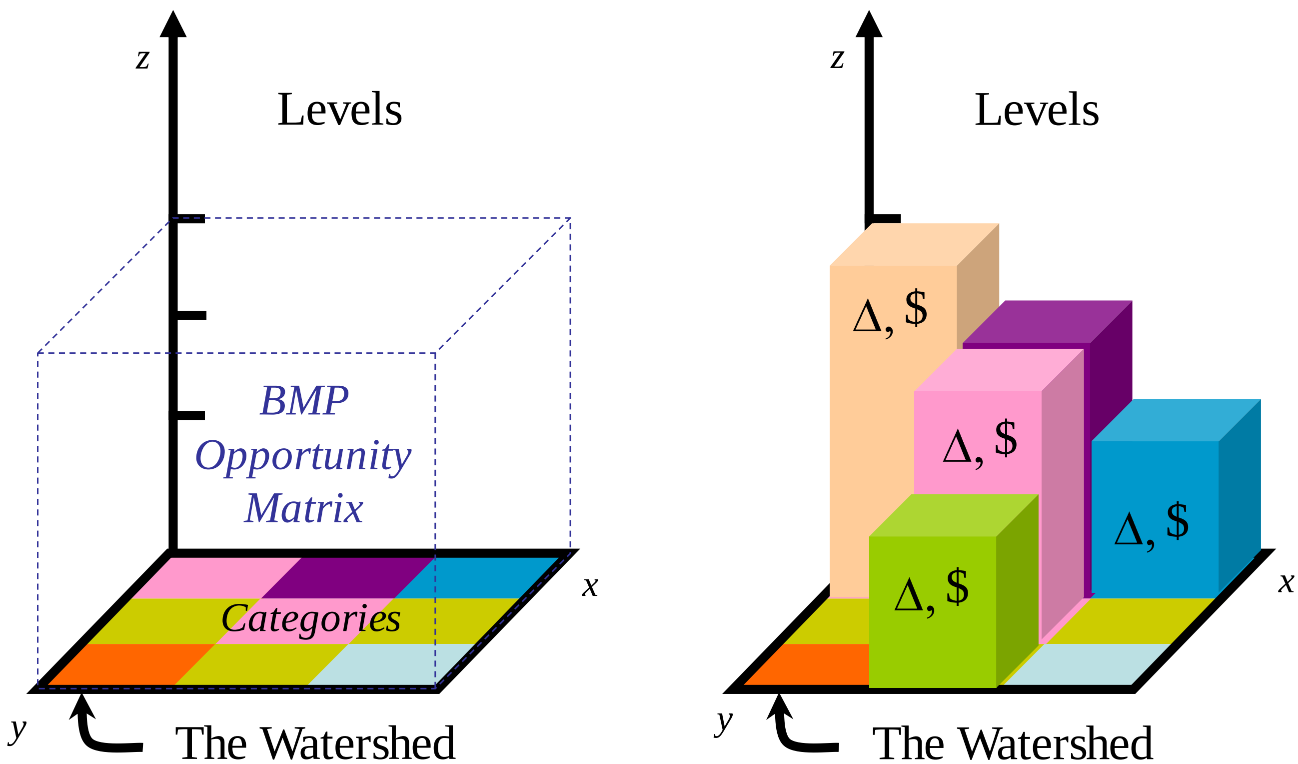

Figure 6. Conceptual relationships between Management Categories and Management Levels.

The following two subsections will provide some additional description of how Management Categories and Management Levels were derived for the Los Angeles County regional watershed study area.

3.2.1 Management Categories

Management categories are generalized descriptions of the key physiographic characteristics of a subwatershed. They are assigned according to hydrologic boundaries (subwatersheds) mainly because their associated attributes will govern the selection and placement of structural BMPs within the subwatersheds. All subwatersheds that have the same management category are likely to have similar opportunities and constraints for selecting and applying BMPs. Numerous characteristics (and permutations or combinations thereof) could be applied to define management categories in Los Angeles County; however, the approach presented here focuses on a few key characteristics that are thought to be the most influential factors.

Extensive GIS and database analyses were performed to determine the key subwatershed characteristics used to classify each of the 2,655 original subwatersheds into a particular management category. Management categories for the Los Angeles County subwatersheds were defined on the basis of the following selected key physiographic characteristics, which directly influence the planning, design, and construction of urban storm water quality improvement projects:

- Impervious cover
- Impervious density configuration
- Land slope
- Road density.

For this analysis, each of these factors was dichotomized for classification by subwatershed. The quantities were normalized by subwatershed, which allowed for meaningful comparison of these factors between subwatersheds.

When the four key characteristics that define the management categories are combined, they form 16 possible combinations. Of those 16, only 9 combinations had subwatersheds associated with them. Table 3 presents the definitions of the nine management category groups. Table 4 summarizes land area distribution associated with each Management Category. Figure 7 shows the classification of each subwatershed into a combined management category group.

Table 3. Definition of Management Categories

ID	Impervious cover	Impervious configuration	Road density	Slope	Code
A	Urban	Concentrated	High road density	Moderate	1110
B	Urban	Concentrated	Low road density	Steep	1101
C	Urban	Concentrated	Low road density	Moderate	1100
D	Urban	Dispersed	Low road density	Steep	1001
E	Urban	Dispersed	Low road density	Moderate	1000
F	Non-Urban	Concentrated	Low road density	Steep	0101
G	Non-Urban	Concentrated	Low road density	Moderate	0100
H	Non-Urban	Dispersed	Low road density	Steep	0001
I	Non-Urban	Dispersed	Low road density	Moderate	0000

Table 4. Summary of land area associated with each Management Category

ID	Code	Area (acres)	Total impervious area (acres)	Urban area (acres)	Impervious urban area (acres)	Pervious urban area (acres)
A	1110	92,083	62,823	89,795	62,610	27,185
B	1101	72,528	19,854	34,371	19,646	14,725
C	1100	346,637	205,573	329,448	203,742	125,706
D	1001	261,072	50,358	146,019	48,733	97,286
E	1000	176,470	67,238	159,709	65,872	93,838
F	0101	53,215	841	1,174	412	762
G	0100	5,138	187	190	115	75
H	0001	928,664	10,458	46,930	4,468	42,462
I	0000	57,387	197	3,067	164	2,902

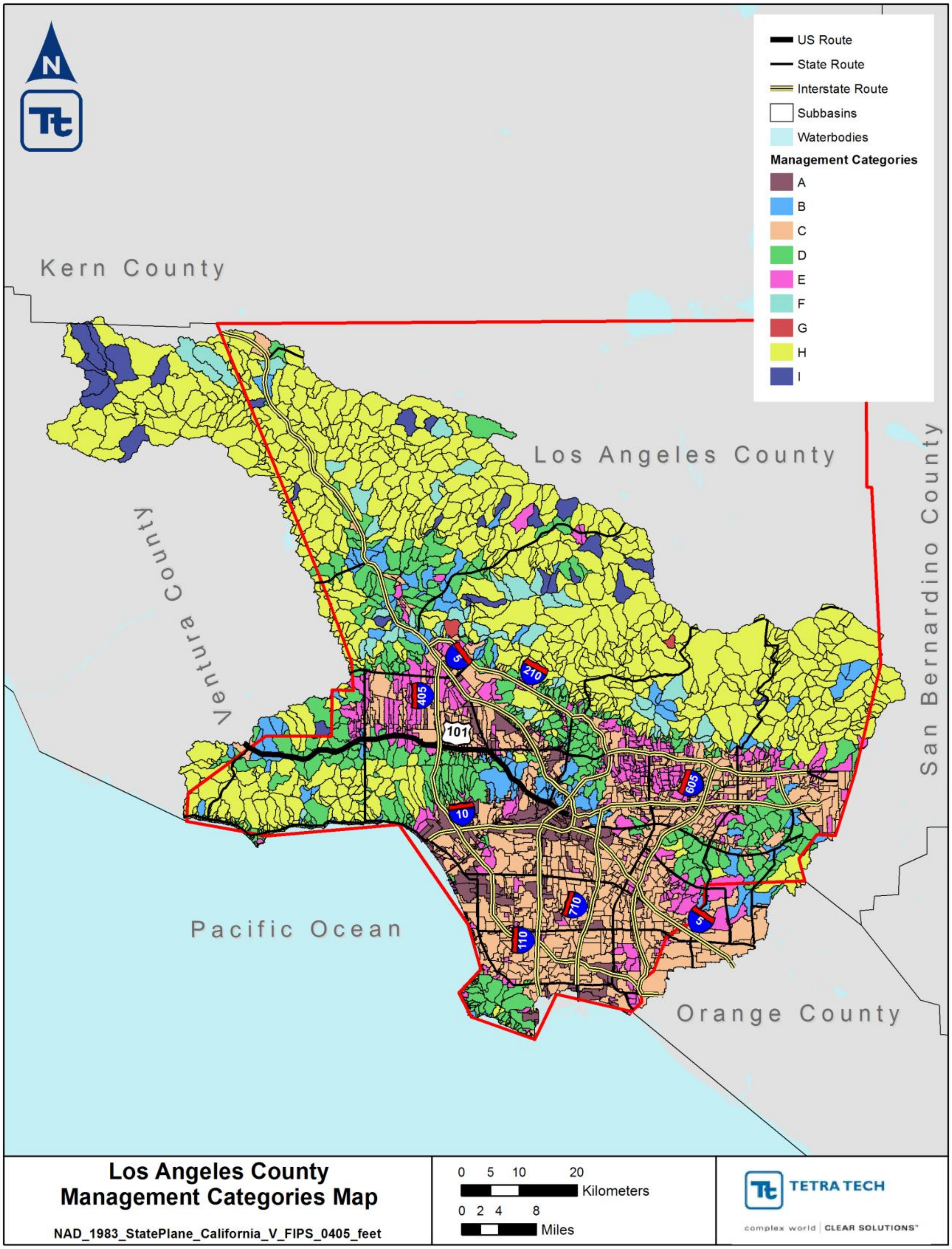

Figure 7. Management categories by subwatershed.

Figure 8 shows the relative distribution of the total watershed area by management category. Figure 9 shows the distribution of the Urban Impervious, Urban Pervious, and Non-Urban areas of each management category.

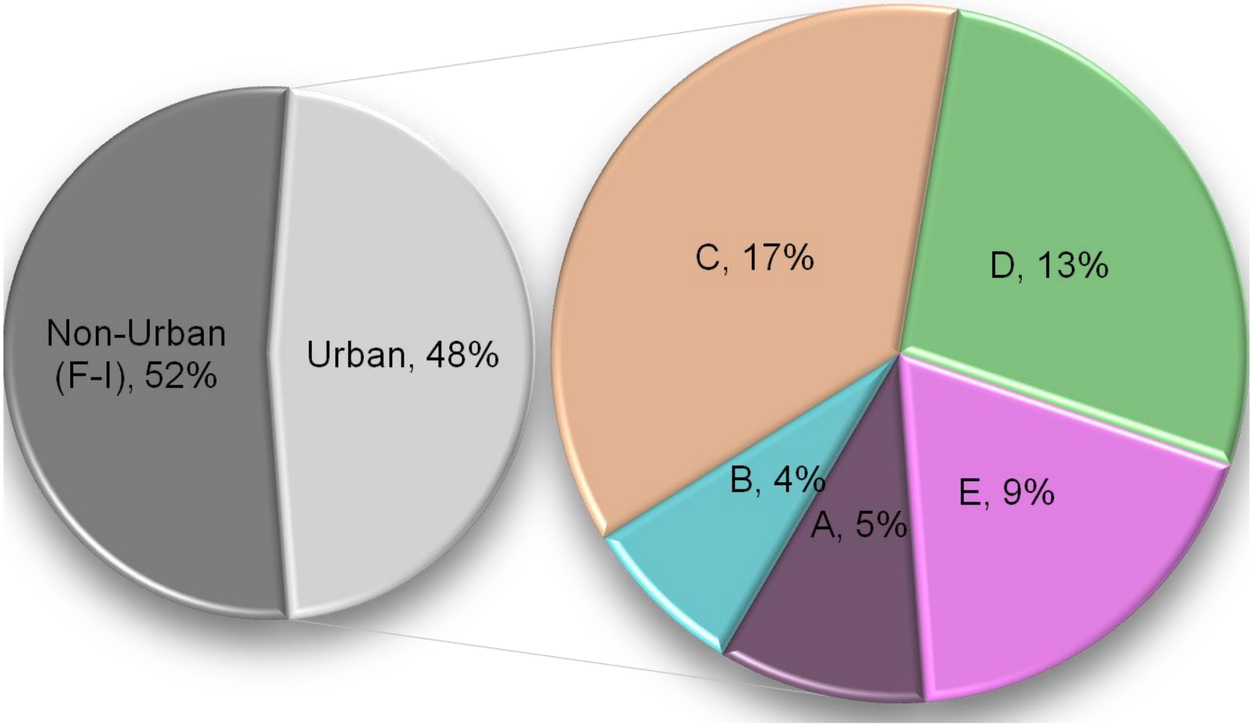

Figure 8. Total area distribution by management category.

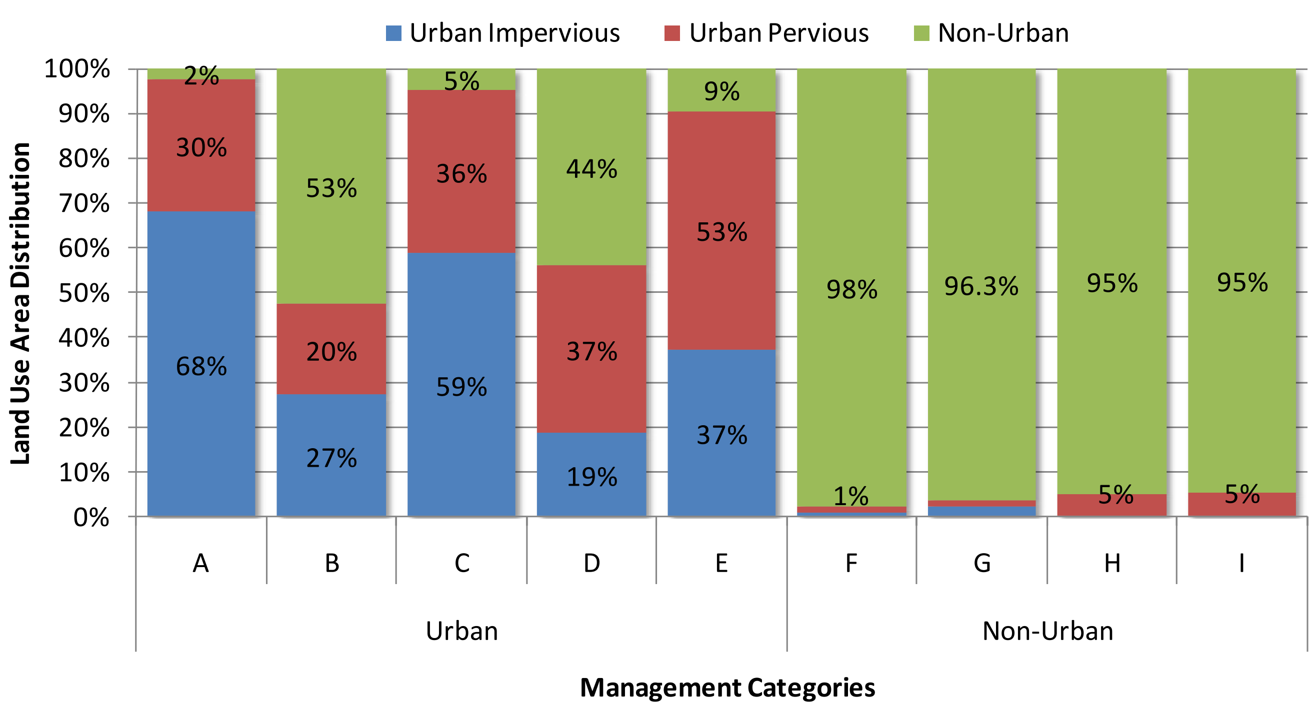

Figure 9. Urban Impervious, Urban Pervious, and Non-Urban area distribution by management category.

3.2.2 Management Levels

The Management Levels concept was used to derive a series of cost-effectiveness curves for every subwatershed in the study area. These cost-effectiveness curves represent the highest expected pollutant reduction benefit at each lowest-cost interval. Management Levels were derived using site-scale models that were configured for representative subwatersheds. EPA's System for Urban Subwatershed Treatment and Analysis Integration (*SUSTAIN*) was used to model BMP performance and cost-benefit optimization for every subwatershed; however, a set of scalable BMP modeling rules were developed using 15 selected subwatersheds and then extrapolated to all other subwatersheds according to their Management Category classification. Figure 10 is an example of a cost-effectiveness curve for a hypothetical subwatershed derived using five Management Level intervals. Management Level 5 represents the maximum feasible treatment that can be achieved using distributed BMPs within a given subwatershed. Management Levels 1 through 4 represent 20 percent intervals of the maximum feasible treatment defined by Level 5.

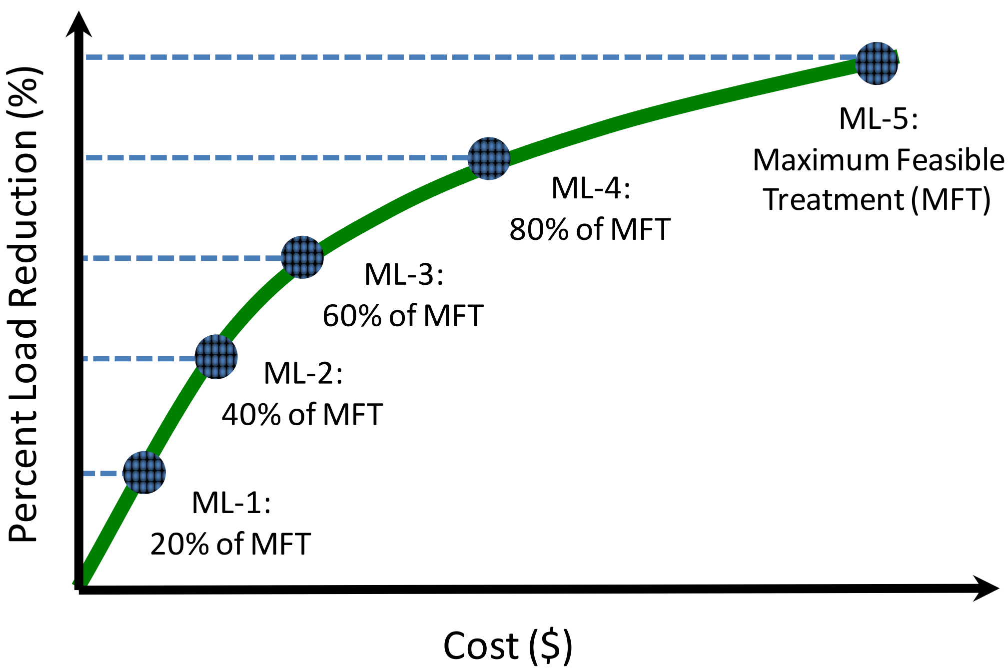

Figure 10. Example of a cost-effectiveness curve derived using five Management Level intervals.

Figure 10 is typical of what is seen in cost-effectiveness curves derived using actual data. Although load reduction percentages are at equal intervals, implementation cost increases non-linearly with increasing reduction. In other words, marginal cost (in dollars per mass removed) increases with increasing load reduction.

3.2.2.1 Selecting Representative Subwatersheds

For each urban Management Category, three representative subwatersheds corresponding to low (5% rank), medium (50% rank), and high (95% rank) runoff potential were used to develop the set of scalable rules. The selection of these representative subwatersheds was based on comprehensive sensitivity analysis of the effects of weather variation, land use variation, and physiographic configuration on modeled hydrologic responses and pollutant loading throughout the watershed. For all modeled subwatersheds, Figure 11 shows the variation in surface runoff within the lower, middle, and upper third rainfall ranges for subwatesheds within each Management Category. Similarly, Figure 12 and Figure 13 show the annual average load of sediment and copper, respectively. In each of these three graphs, the average precipitation value for each "one-third" bin is indicated in the precipitation series. A review of these summary results provides some general insight into the behavior and response throughout the watershed. For example, the higher the precipitation, the higher the runoff and pollutant loads. The most impervious Management Categories also show the highest overall runoff and pollutant load levels. The non-urban Management Categories (F-I) report the highest overall sediment loads (Figure 12); however, they have the lowest copper loads (Figure 13). This is because metals were modeled as being primarily associated with urban sediment, which is consistent with local monitoring data. The highest rainfall bin for Management Category B has a lower median and mean runoff than the second-highest bin, but has the highest unit-area sediment load of all urban Management Categories. Recall that Management Category B is described as having concentrated impervious configuration, low road density, and steep slopes. These types of subwatersheds have pockets of urbanization surrounded by relatively vacant, steeply sloped terrain. The sensitivity analysis provided a sound basis for selecting representative subwatersheds for each Management Category.

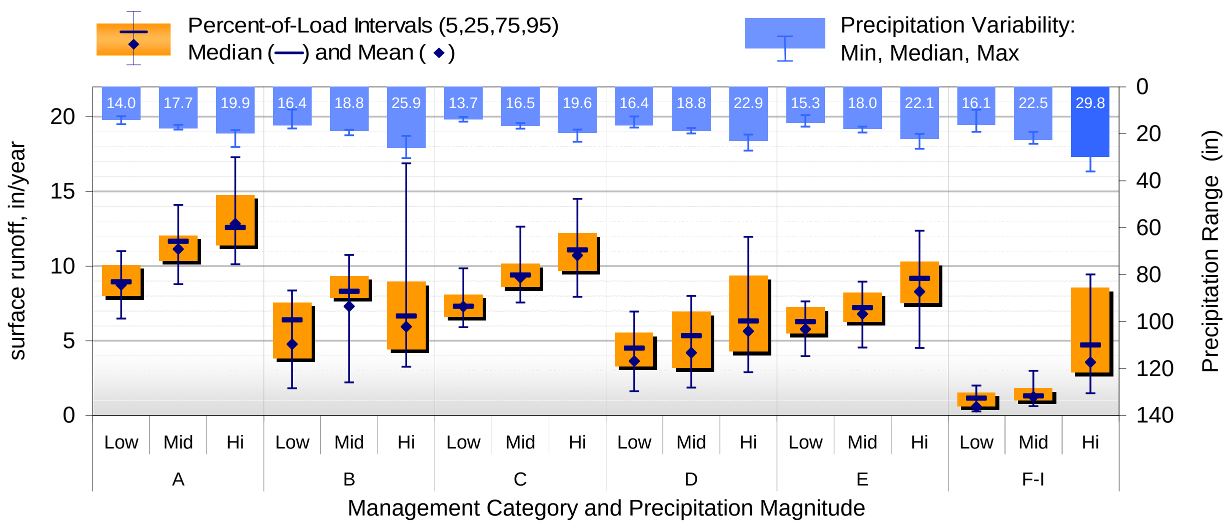

Figure 11. Average annual load ranges by Management Category and precipitation range for surface runoff, in/year.

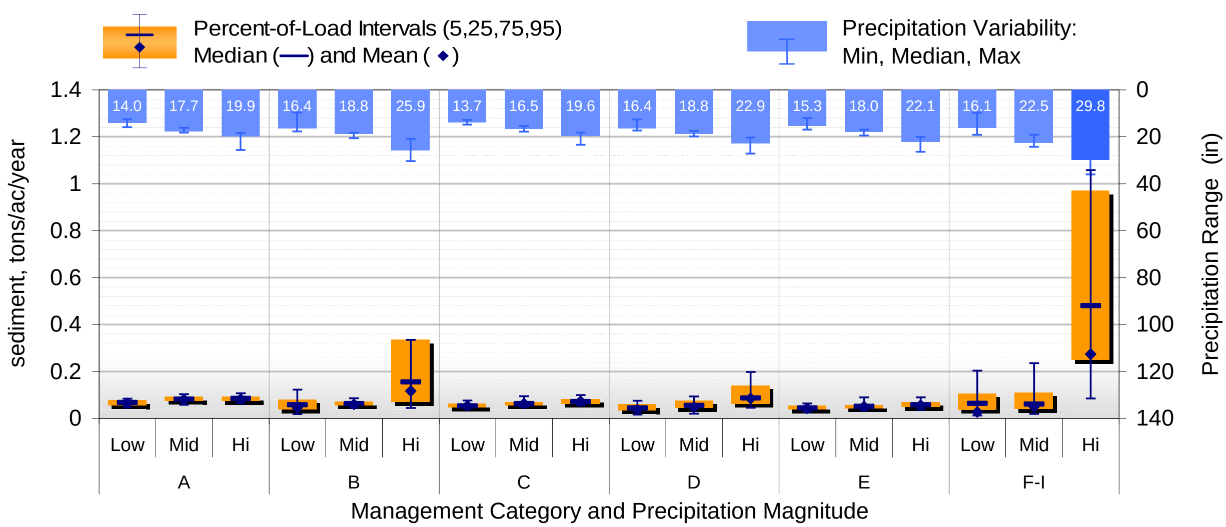

Figure 12. Average annual load ranges by Management Category and precipitation range for sediment, tons/ac/year.

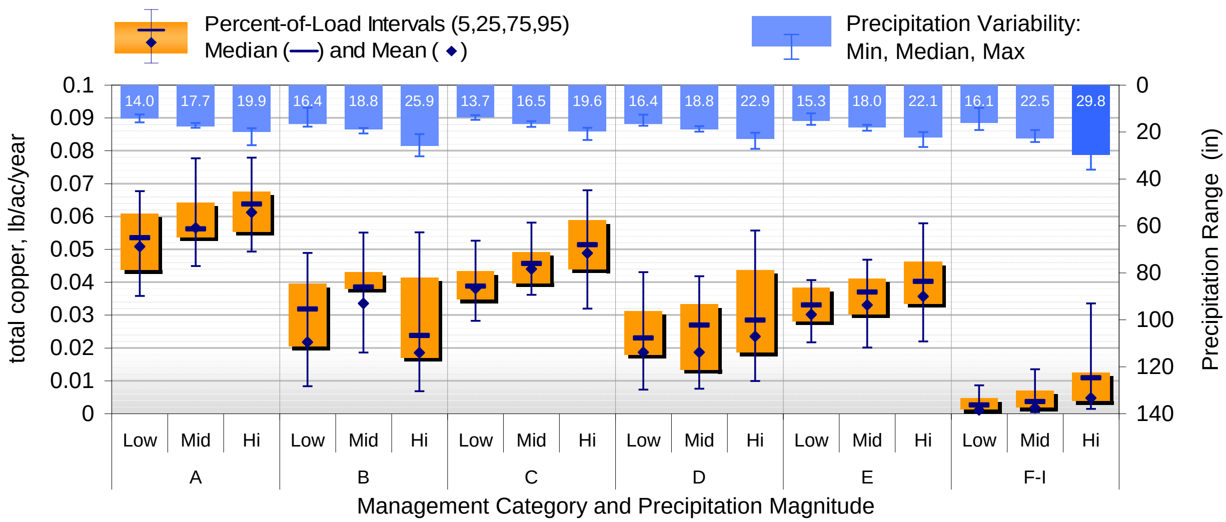

Figure 13. Average annual load ranges by Management Category and precipitation range for total copper, lb/ac/year.

For each urban Management Category (A–E), one subwatershed was selected from each bin. The list of selected representative subwatersheds is presented below as Table 5. Category C is highlighted in the table for further discussion because 20 percent of the study area (which is nearly half of all urban area) is categorized as Management Category C. Figure 14 is a map-and-graph panel showing the location of these three watersheds, as well as the relative land use (HRU) distribution with each subwatershed. By selecting watersheds that span a range of runoff potential, the analysis implicitly incorporated estimates of variance in both loading and runoff conditions consistent with Recommendation 1, summarized previously from the SCCWRP study. As previously stated, the modeling effort also extended the range of constituents under consideration to include total nitrogen, total phosphorus, total suspended solids, copper, zinc, lead, and fecal coliform.

Table 5. List of selected subwatersheds by runoff potential for each Management Category

Management Category	Selected subwatersheds by runoff potential		
	Low (5%)	Medium (50%)	High (95%)
A	6044	1073	6370
B	5332	1088	1090
C	5164	6057	2028
D	4142	5088	6136
E	6445	6934	1216

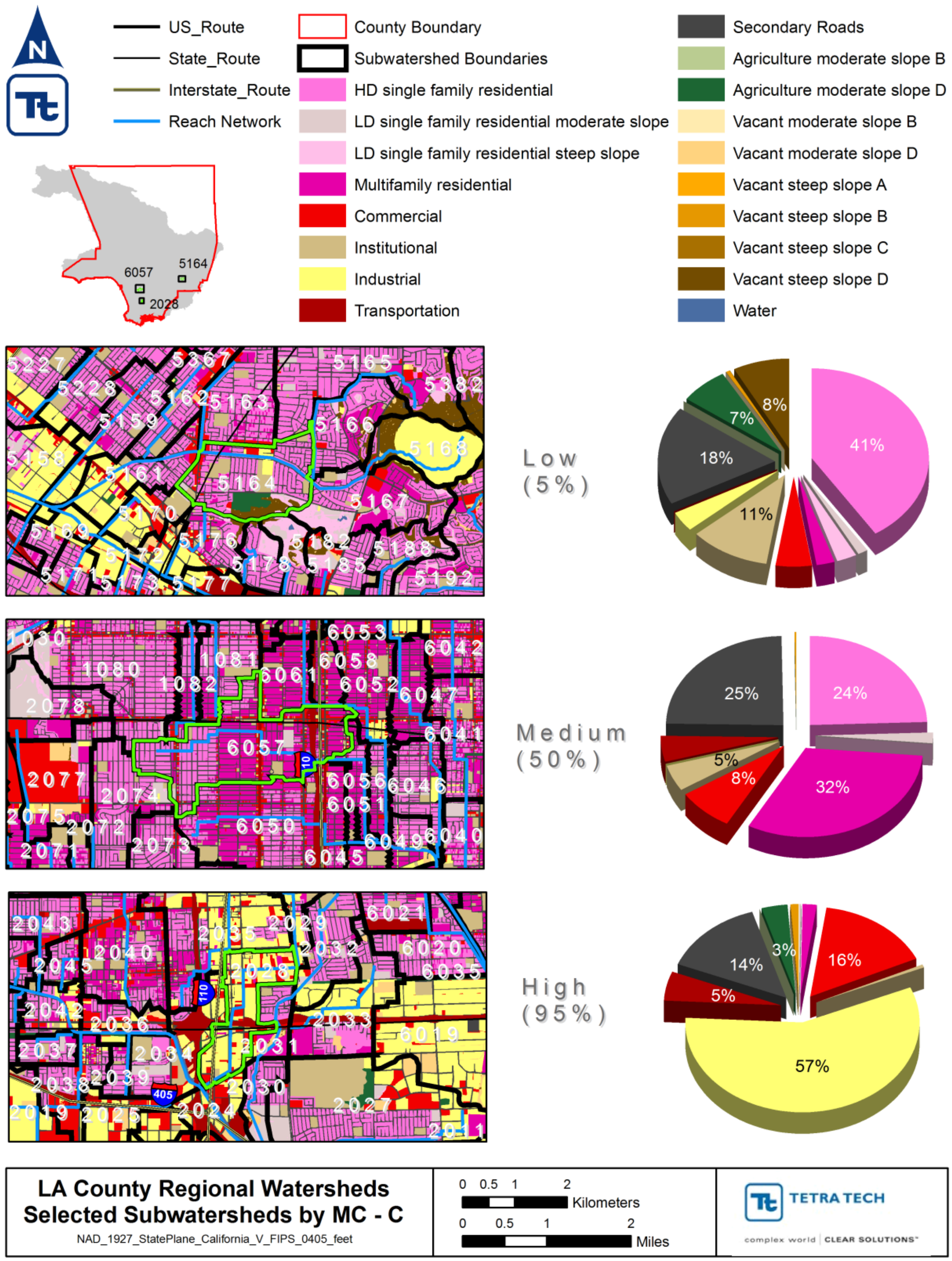

Figure 14. Selected representative subwatersheds for Management Category C.

3.2.2.2 Distributed BMP Representation

The distributed structural BMP types considered most appropriate for implementation in Los Angeles County are (1) pervious pavement, (2) bioretention, and (3) rain barrels. They are applied as a function of land use. A generalized schematic of the treatment pathways for all Management Categories is presented as Figure 15.

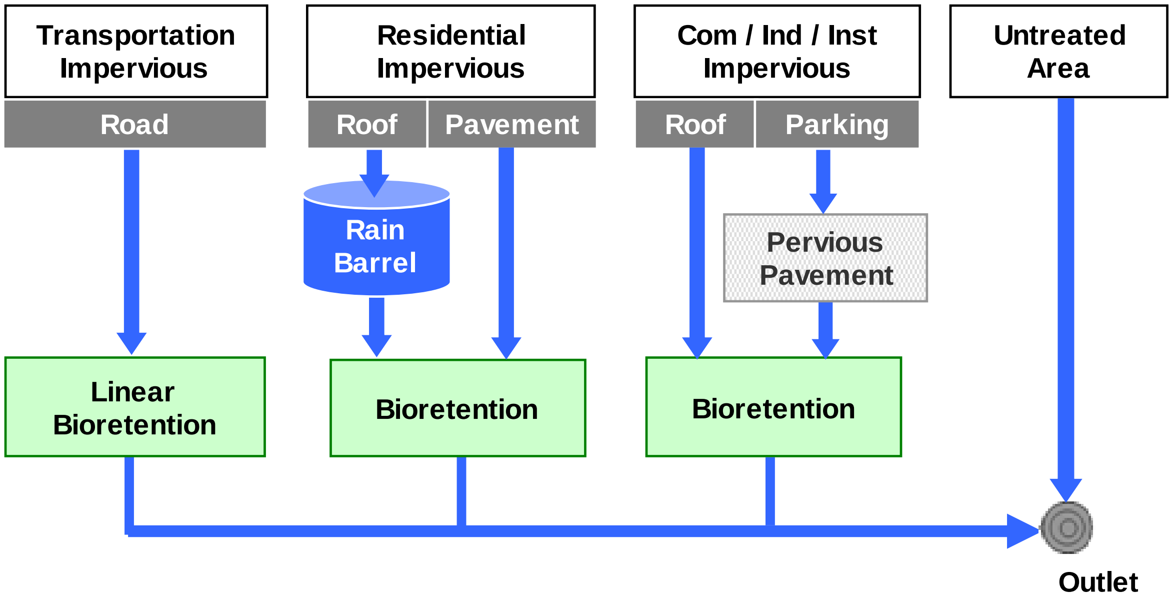

Figure 15. Generalized treatment pathways framework for defining Management Levels.

Depending on the relative HRU/land use distribution of a particular subwatershed, the degree to which each treatment pathway is used varies. For each representative subwatershed, a hypothetical model was configured with the actual drainage area HRU distribution normalized to 100 acres.

To summarize, the methodology for determining Management Level rules consist of two components: (1) the BMP utilization percentage and (2) the BMP design depth multiplier. The BMP utilization percentage indicates the percent of the maximum achievable treatment area (for distributed BMPs); the BMP design depth multiplier indicates the BMP storage depth for the treated area. This multiplier is also a function of precipitation intensity for each subwatershed.

For every Management Level, the BMP utilization percentage and the BMP design depth multiplier were translated into the number of units (NUMUNIT) and size of each BMP (SIZE) components, respectively, using the following two equations:

NUMUNIT = (BMP utilization percentage) x (max number of units)
SIZE = (85^{th}% rain depth) x (BMP design depth multiplier / 1.5) x (max size).

Note that the 85^{th} percentile rainfall depth was used as the normalizing storm for the SIZE component.

Finally, investigation of the optimized treatment capacity distribution among the three land-use-based pathways shown in Figure 15 gives some insight into how BMPs are prioritized based on land use distribution. Figure 16 is a graph of treatment capacity by land use and Management Level for each of the three selected MC-C representative subwatersheds, previously shown in Figure 14 . Figure 16 shows that the treatment capacity for commercial/institutional/industrial and transportation land uses are prioritized over residential. This stands out even more at lower Management Levels. The reason for this is that residential land uses have lower unit area pollutant loadings relative to the other two; therefore, it is more cost-effective to prioritize higher-loading areas for management activity because the most notable impact results from the BMP investment made.

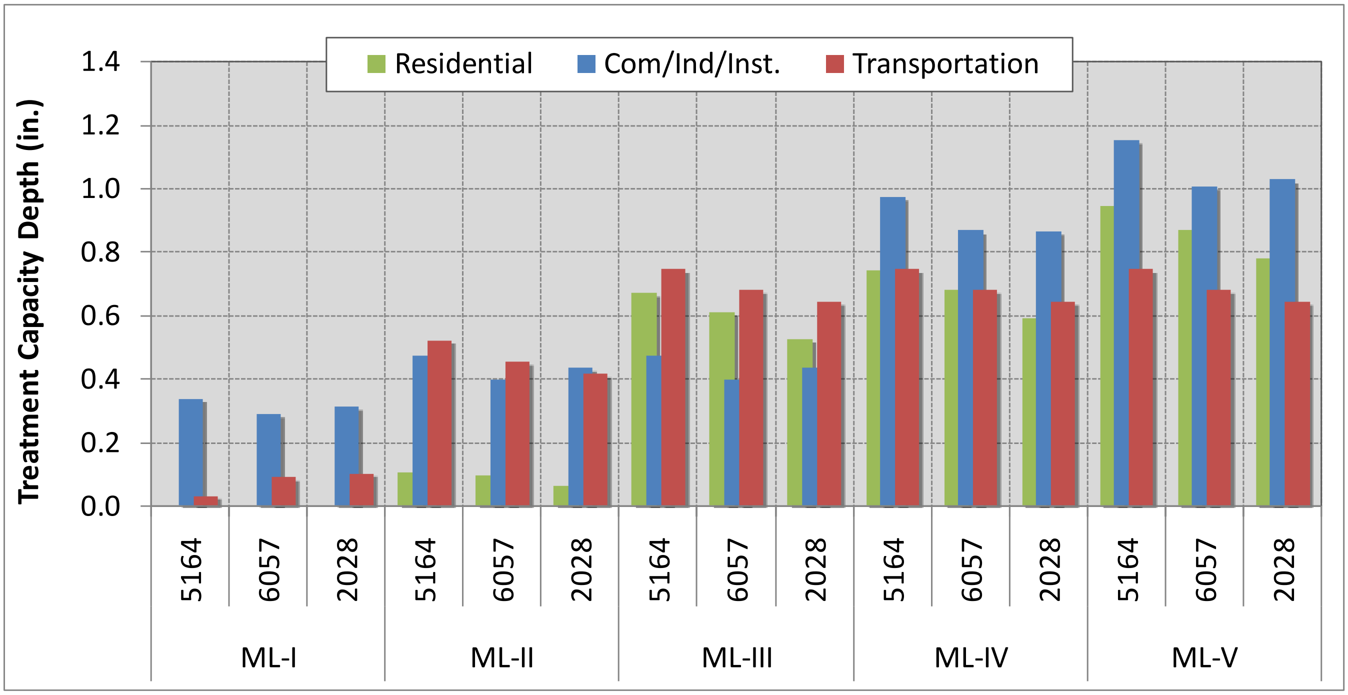

Figure 16. Land use treatment capacity by Management Level for selected Management Category C subwatersheds.

3.2.2.3 Distributed BMP Cost Functions

The costs estimates are based on values derived from the LACDPW bid history and local vendors serving Los Angeles County. For comparison purposes, an extensive literature search (EPA 2003, Brown and Schueler 1997, Coffman et al. 1999, CASQA 2003, Hathaway and Hunt 2007, Landphair et al. 2000, NCHRP 2005) was performed to identify existing cost functions for the BMP types previously shown in the Figure 15 schematic. Where local data were not available, literature sources were used. The cost functions for distributed BMPs are twenty-year lifecycle costs that include: (1) initial construction cost (year 0) and (2) operation and maintenance (O&M) costs (annualized present value for year 1 through year 20). No land acquisition costs are included because it was assumed that distributed BMPs would be implemented on private land by the respective land owner or trustee. An interest rate of 5 percent (commonly accepted value) was used to convert twenty-year annual costs to present value.

Construction costs can be estimated using the following generic equation by applying the cost assumptions for construction processes and components:

where L = length of BMP (ft); A = surface area of BMP (ft^2); V_t = total volume of BMP (ft^3); V_m = media volume of BMP (ft^3); V_u = underdrain volume of BMP (ft^3). The a_x coefficients are unique by BMP type and location. BMP design, project planning, and construction mobilization costs are assumed to be proportional to *Construction Cost*. For this study it these costs were assumed to be 60% of the construction cost based on the recent Los Angeles County local vendor bid history.

Pervious pavement annual O&M cost were assumed to be $0.0059 per square foot in 2009 dollars (EPA 1999), while bioretention O&M costs were assumed to be 4 percent of the construction cost (CASQA 2003). O&M costs for rain barrels were assumed to be negligible and were therefore not considered. Table 6 shows the twenty-year lifecycle cost components that were used in the model. As BMP sizes varied during optimization to derive the Management Levels, these cost components were applied to calculate the associated costs accordingly.

Table 6. Twenty-year lifecycle cost components for distributed BMPs

Land Use	BMP	Area Cost ($/ft^2)	Total Volume Cost ($/ft^3)	Media Volume Cost ($/ft^3)	Underdrain Cost ($/ft^3)
Transportation	Bioretention (without underdrain)	11.206	3.31	5.83	0
Residential	Rain Barrel	0	34.40	0	0
	Bioretention (with underdrain)	13.241	3.31	5.83	4.04
Commercial, Industrial, Institutional	Pervious Pavement (without underdrain)	21.994	0	0	3.08
	Bioretention (with underdrain)	13.241	3.31	5.83	4.04

3.3 Continuous Simulation and Optimization BMP Design Approach

The previous sections have described the modeling approach and analytical considerations associated with the modeling platform being used for this analysis. One must consider the differences between the traditional BMP design storm approach for sizing BMPs versus one based on continuous simulation and optimization. The traditional BMP design process typically involves using a preselected design storm to determine BMP sizes. This design storm is usually selected based on runoff volume and/or flood prevention criteria. The traditional design storm is not based on water quality or TMDL attainment criteria; nonetheless, it might be possible to quantify water quality benefit associated with the design after the fact. Figure 17 is a conceptual illustration of the traditional design storm approach for deriving BMP treatment capacity.

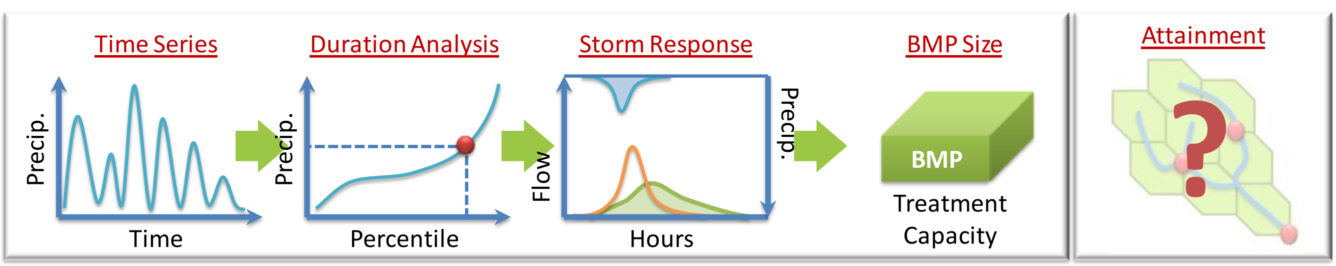

Figure 17. Traditional design storm approach for deriving BMP treatment capacity.

The traditional design storm approach can be described as follows:

1. Evaluate time series of precipitation that span a long enough period of time to characterize a wide range of precipitation magnitude and frequency.
2. Statistically summarize the precipitation (using rainfall duration, or similar analysis) to determine return period and associated magnitude.
3. Apply a typical design storm distribution to the selected rainfall magnitude to develop a design storm.
4. Using the design storm, apply a storm response model or methodology (such as TR-55) to size the BMP according to a desired performance response.
5. The derived BMP size is analogous to the treatment capacity.

Note that there is no direct link to in-stream water quality attainment in the traditional design storm approach. It is possible to quantify water quality benefit associated with the derived treatment capacity; however, a uniform sizing rule might be overly protective in one area and inadequate in another. Furthermore, in terms of water quality attainment, a uniform sizing rule might not be protective of attainment for multiple pollutants.

On the other hand, a continuous simulation and optimization BMP design approach offers some advantages over the traditional design storm approach. Figure 18 is a conceptual illustration of this approach.

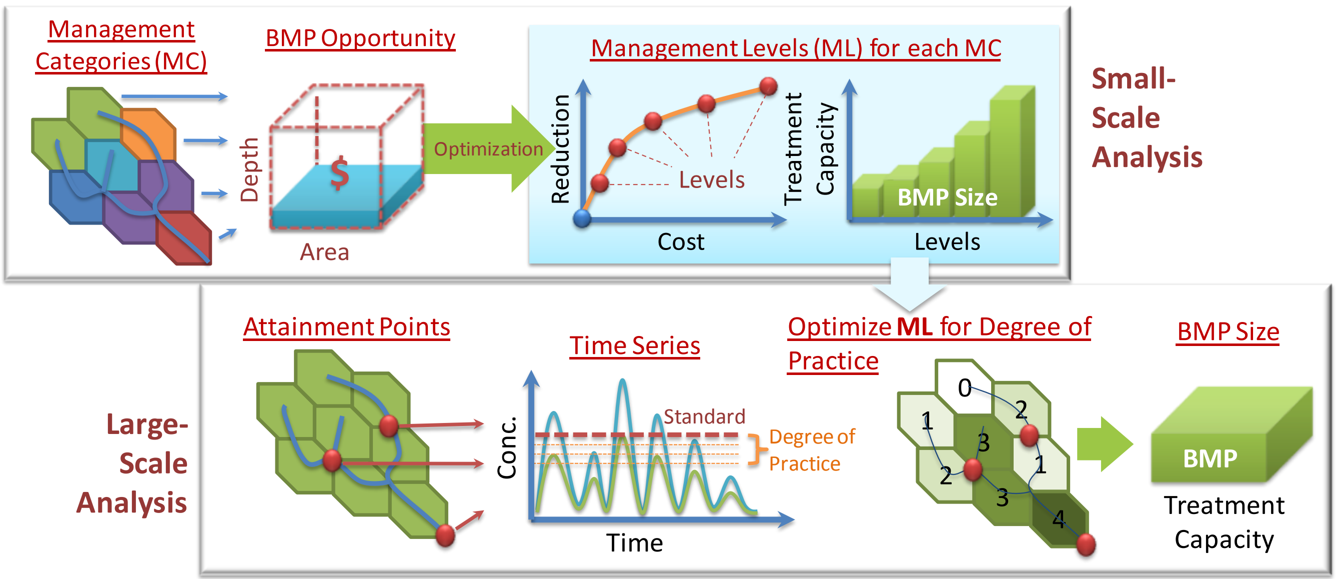

Figure 18. Continuous simulation and optimization BMP design approach for deriving BMP treatment capacity.

The continuous simulation and optimization BMP design approach can be divided into two steps: (1) small-scale BMP optimization to derive Management Levels and (2) large-scale optimization of Management Levels based on TMDL attainment. The approach is outlined as follows:

<u>Small-Scale Analysis</u>:

1. Organize subwatersheds into Management Categories according to unique watershed characteristics that most influence the type of management that will be selected.
2. Identify potential BMP opportunity (volume = area x depth) and tabulate associated costs.
3. Derive Management Levels for each Management Category: Use cost-benefit optimization to derive a cost-effectiveness curve of the BMP opportunity space (maximum reduction at minimum-cost intervals). Each Management Level has a fixed BMP treatment capacity.

<u>Large-Scale Analysis</u>:

1. Determine the existing condition concentrations and water quality standards at each attainment point (by location and pollutant combination).
2. Set desired Degree of Practice for water quality attainment. This is an allowable wet-weather exceedance criterion (risk tolerance) for each water quality standard for each location.
3. Determine the optimum Management Level required to satisfy attainment at the specified Degree of Practice.
4. The resulting Management Level for each subwatershed can be translated into BMP treatment capacity (BMP size).

The objective of the traditional design storm approach for BMP design is to derive BMP sizes (treatment capacity). Each Management Level in the continuous simulation and optimization BMP design approach also has a unique treatment capacity associated with it. The large-scale BMP optimization process results in a specified combination of Management Levels by subwatershed that is required to achieve attainment at the desired Degree of Practice. Both methods arrive at BMP treatment capacity as a product; however, the traditional design storm approach does not directly address attainment.

Very practical and necessary uses for the traditional design storm approach that cannot be entirely replaced by this continuous-simulation-based approach still remain. Although treatment capacity can be determined from the continuous simulation and optimization BMP design approach, certain flow-based design details, such as the design of BMP outlet structures to manage ponding time, should still be sized according to certain design criteria. Therefore, some combination of these two approaches must ultimately be considered in order to satisfy both flow-based and volume-based criteria.

4 Degree of Practice and Model Uncertainty

The large-scale watershed optimization model is formulated on the basis of the dynamic watershed simulation model for the Los Angeles County regional watersheds. The purpose of the optimization model is to find the optimal distribution of BMP treatment capacity within each of the 2,655 subwatersheds such that the TMDL targets for total nitrogen, total phosphorus, total copper, total lead, and total zinc are simultaneously met at the lowest possible BMP implementation cost. Therefore, a critical component of the optimization model formulation is to establish a linkage between TMDL targets and BMP performance measures.

In the Lost Angeles County regional watersheds, the TMDL targets for the pollutants are defined on a concentration basis, while the BMP performance is usually measured as a load reduction ratio. For this analysis, it was necessary to devise a way to represent the concentration target in terms of load reduction. The most straightforward way was to first locate the highest concentration of each pollutant under the baseline condition and then calculate the needed reduction ratio for bringing the maximum concentration down to the target concentration as the targeted BMP performance level. That method essentially assumes that the TMDL target concentrations need to be met all the time, including during extreme events (which could be beyond the controllable range practicable with human management activities). It could be plausible to devise policy and a management plan to allow a certain number of exceedances to occur under extreme conditions—in fact, some water quality criteria permit some quantity of allowable exceedances.

In the context of this cost-benefit optimization application, allowable exceedances can help to avoid the significant costs associated with controlling extreme events. Furthermore, using a single extreme value to derive the reduction target neglects the fact that the watershed simulation model is a simplified representation of the real system. The model inherently simulates concentrations that are subject to uncertainty. Therefore, a scientifically sound and practically effective, watershed-scale management and BMP implementation scheme is most effectively conducted on a time-variable basis and in an adaptive manner to progressively reduce uncertainty in the decision-making process.

Instead of developing an optimal management scheme based on a single-value TMDL target-BMP performance linkage, we propose to devise a series optimal management scheme with multiple degrees of Practice. The highest Degree of Practice would be the one using the maximum baseline concentration to derive the target reduction ratios. Lower Degrees of Practice would allow a certain percentage of exceedance. This approach facilitates an adaptive management approach for the Los Angeles County watersheds while providing a platform with the potential to meaningfully evaluate and quantify the Maximum Extent Practicable (MEP) management plan.

Five Degrees of Practice have been defined for this analysis. Table 7 defines the wet-weather allowable exceedance (risk tolerance) and TMDL attainment values associated with the five Degrees of Practice.

Table 7. Degree of Practice wet-weather allowable exceedance and attainment

Degree of Practice	Wet-weather allowable exceedance (percent of time)	Wet-weather TMDL attainment (percent of time)
I	25%	75%
II	15%	85%
III	10%	90%
IV	5%	95%
V	0%	100%

To compute these metrics, first the *LSPC* model was run for 10 years under baseline conditions (with no reduction applied). Next, a baseflow separation analysis (using the fixed-interval method) was conducted to distinguish wet-weather days from dry days. A surface flow threshold of 10 percent was used to distinguish flow regimes. In other words, wet/storm days were those where hydrograph-separated surface flow was greater than 10 percent of the total flow. Once the storm dates were identified, a concentration-duration curve was derived for each attainment point and pollutant combination. From the concentration-duration curve, one could readily obtain the 85th, 90th, and 95th percentile and maximum modeled concentrations for each attainment point (Degrees of Practice). For each model reduction scenario, those concentrations could then be readily compared with the TMDL target concentrations to determine attainment or nonattainment at the specified location for each pollutant of concern.

The primary objective is source control through the use of distributed stormwater management. However, as Degree of Practice increases, it is recognized that additional measures might be needed to achieve attainment. For this reason, the volume of additional centralized storage required for attainment can be computed for subwatersheds upstream of attainment points. Once application of distributed BMPs has been exhausted, this additional volume is computed on a subwatershed basis.

For all wet-weather events, the 75th percentile concentrations of the five pollutants were also used to calculate the targeted reduction ratios at each of the attainment points for Degree of Practice I (where wet-weather TMDL attainment occurs 85 percent of the time). Similarly, the 85th, 90th percentile, 95th percentile, and 100th percentile values were used to calculate targeted reduction ratios for Degrees of Practice scenarios II through V. With the calculated target reduction ratios at each attainment point, the large-scale optimization model was formulated to obtain optimal BMP treatment capacity for each Degree of Practice. As Degree of Practice increases (enforcing a higher in-stream percent wet-weather attainment), cost is expected to increase exponentially, as conceptualized in Figure 19. This information can be used to both (1) target and prioritize implementation areas and (2) serve as a platform for evaluating cost-effective Degrees of Practice that define the most cost-effective practice.

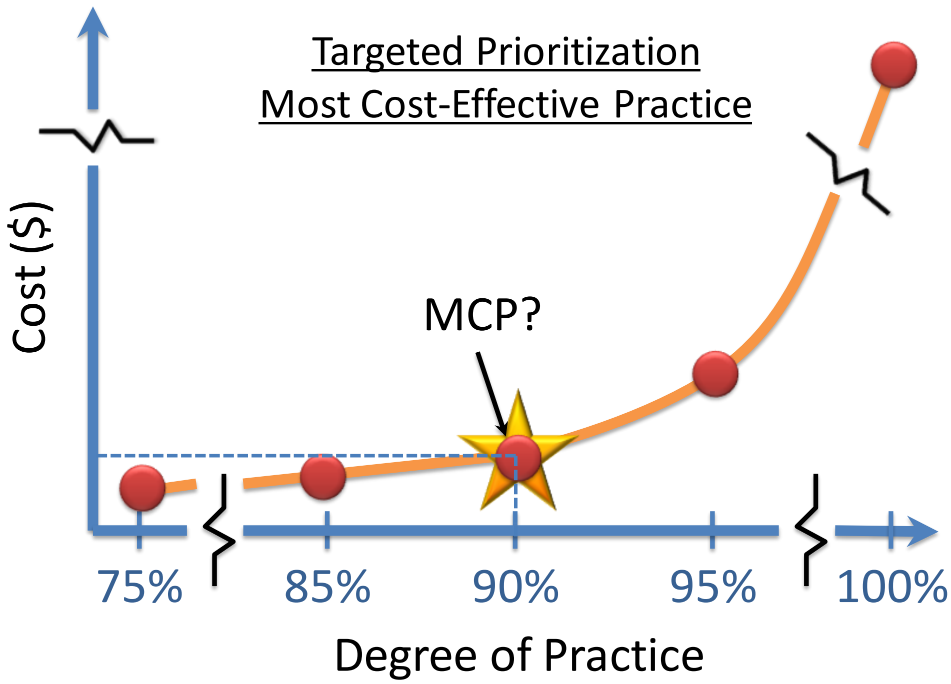

Figure 19. Theoretical graph of cost versus Degree of Practice for targeted prioritization and defining MCP.

5 Model Results

The model results are divided into three sections. The first section presents a brief summary of standard attainment under baseline conditions. The second section illustrates the BMP search space opportunity defined by the proportional selection of distributed BMPs and augmented by centralized BMPs as needed to achieve each attainment target. This section also includes a scenario defined by centralized BMPs only. The third section identifies a critical storm within the time series and illustrates the BMP performance by showing how the hydrograph and pollutographs change with increasing Management Level at a given location for the same storm.

5.1 Baseline Condition Attainment Evaluation

Spatial TMDL attainment was illustrated at each attainment point as either meeting (green dot) or exceeding (red dot) the in-stream criteria. At some locations, multiple standards apply. A point is shown as green only when *all* criteria at a given point have been met. Figure 20 shows baseline TMDL attainment under Degree of Practice I, while Figure 21 shows baseline attainment under Degree of Practice V. A couple of interesting trends can be seen in these figures. First, under Degree of Practice I, most of the exceedances are concentrated along the main stem Los Angeles and San Gabriel rivers. The number of locations required to satisfy 85 percent TMDL attainment is far fewer than the total number of attainment points. Second, under Degree of Practice V, there are two listed tributary segments for which the model shows 100 percent attainment. These were found to be for TN (in Malibu Creek) and Pb (on a San Gabriel River tributary). This indicates that the model shows 100 percent attainment at these locations under baseline conditions, suggesting that either (1) the model is underpredicting the actual levels at those locations or (2) the listed standard is either not correct or not exceeded during the modeling period. Additional analysis was performed to confirm the nature of these observations.

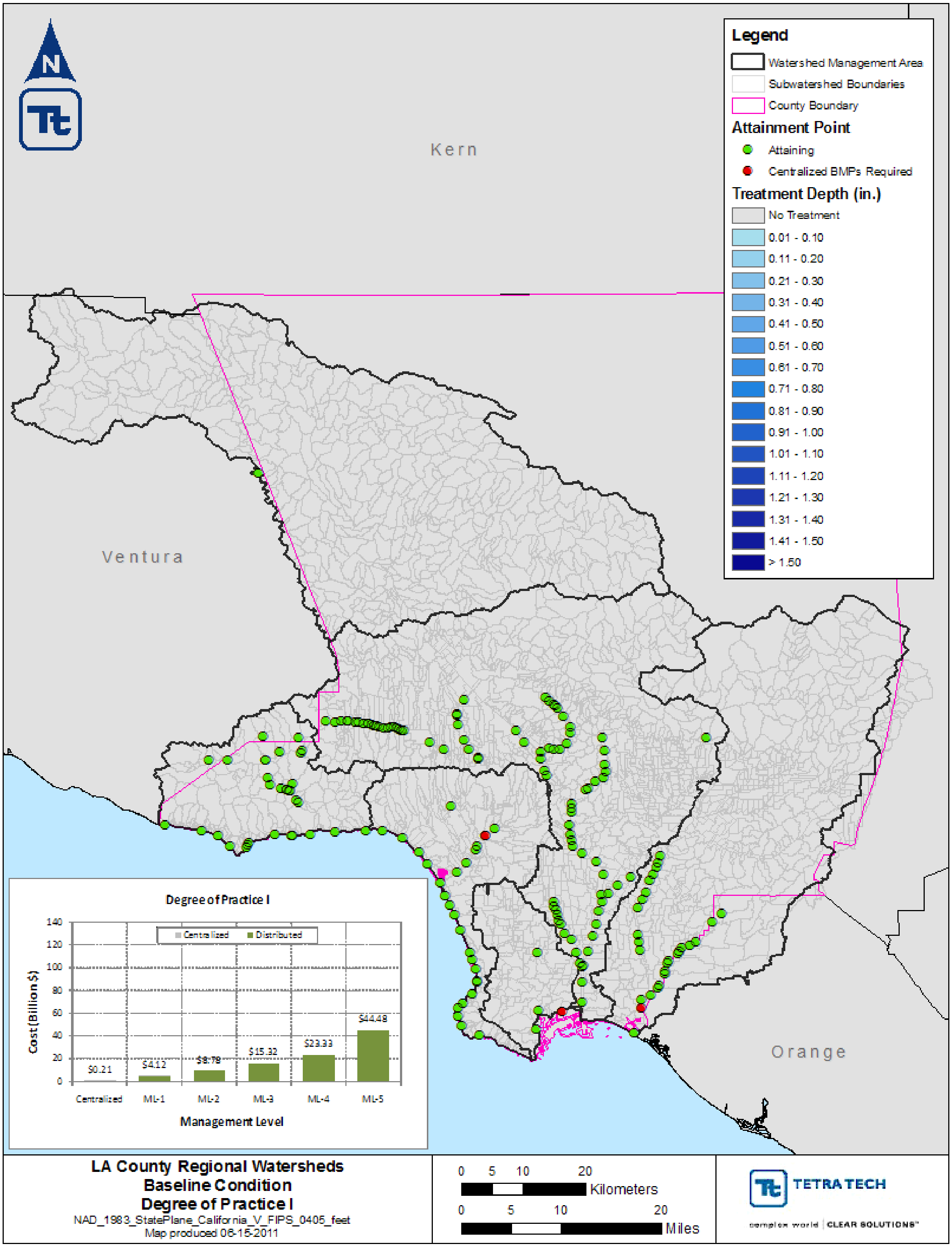

Figure 20. Baseline TMDL attainment (with required centralized BMP locations) under Degree of Practice I.

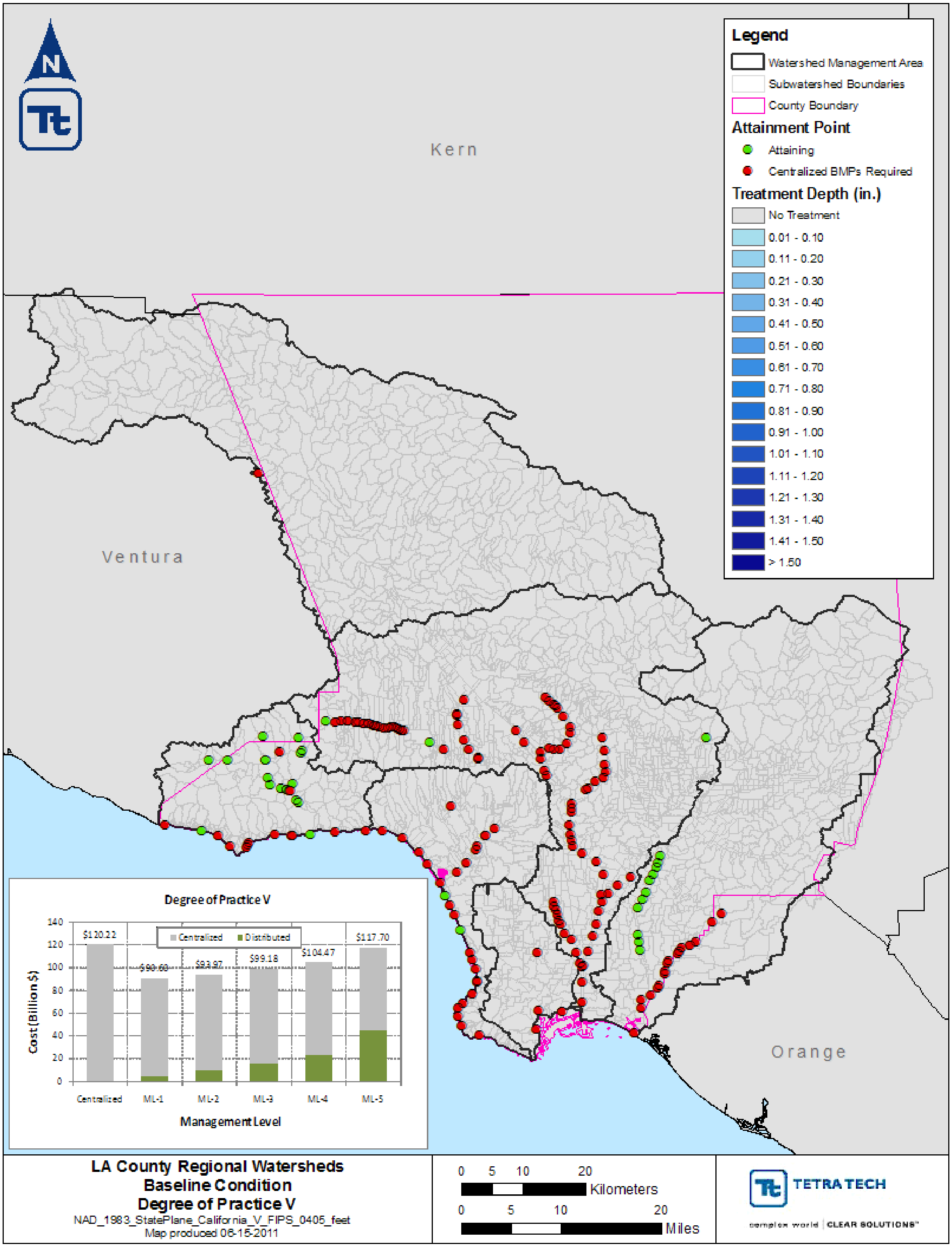

Figure 21. Baseline TMDL attainment (with required centralized BMP locations) under Degree of Practice V.

Some points showed attainment at all Degrees of Practice. For the Malibu Creek watershed, the nitrogen criteria seem to be much higher than what is observed and also than what the model predicts for those areas. All in all, because copper and zinc tend to be the limiting pollutants that drive optimization, these two anomalies for lead and nitrogen in two specific tributaries are most likely inconsequential to the overall outcome and conclusions of this study. In Figure 21, there were two points in the stream network where the lead standard was evaluated against the modeled time series. Figure 22 shows lead TMDL attainment in the San Gabriel River watershed for a stream where the modeled result never exceeds the lead standard. Figure 23 shows a similar attainment point in the Los Angeles River watershed, except that there are several exceedances observed at this location. One reason for the difference is clearly seen as the difference in the standards themselves. The San Gabriel standard is over 160 ug/L, whereas the Los Angeles standard is closer to 60 ug/L. This dramatic difference in standard needs further investigation because there does not appear to be a land-use-based source upstream of San Gabriel that is potentially a higher lead-loading land use than what would be found in the Los Angeles River watershed.

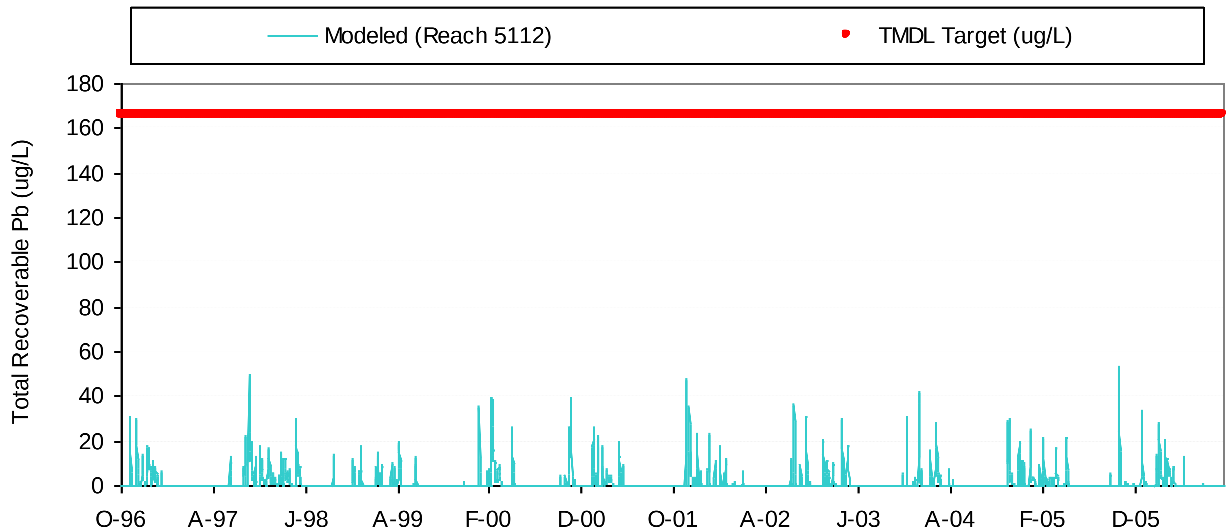

Figure 22. Lead attainment assessment at San Gabriel watershed, segment 5112.

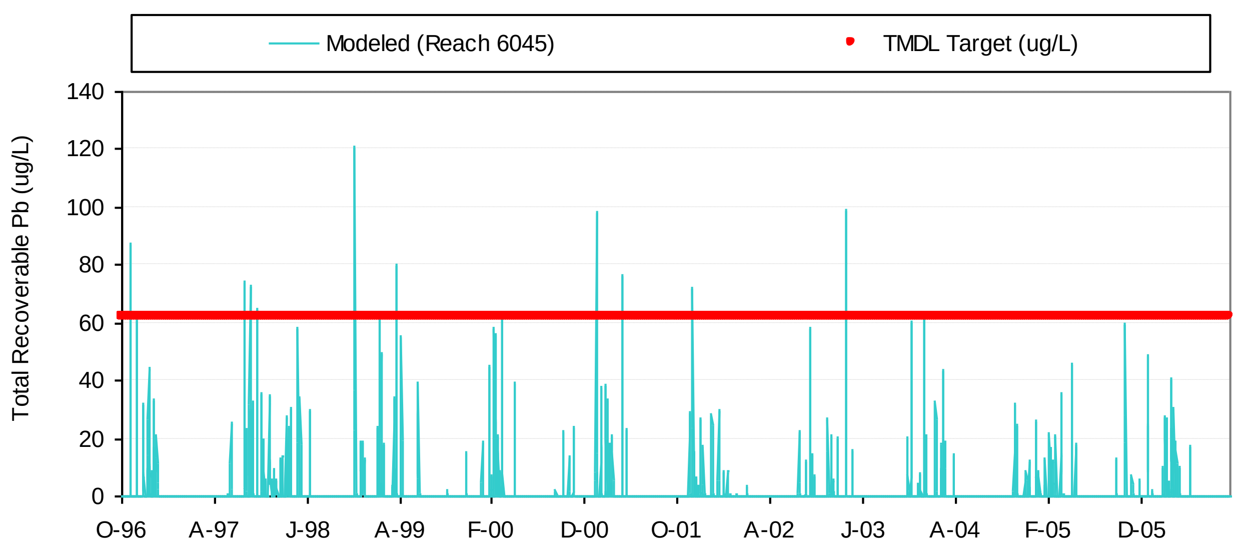

Figure 23. Lead attainment assessment at Los Angeles River watershed, segment 6045.

5.2 Centralized BMP Attainment Evaluation

The construction of large centralized BMP facilities was also considered in this study. Data analysis and model sensitivity testing both suggest that it is impossible to achieve 100 percent attainment at all locations using only distributed BMPs. An analysis of all available centralized BMP data (size, configuration, and expected performance) was performed. In addition, it was recognized that land acquisition is often necessary for placement and construction of these facilities. An average land cost of $2.55 million/acre was used to calculate land cost (Cutter et al. 2008).

Depending on where the centralized BMP is placed, the performance and potential capture volume changes. Construction costs were calculated using the relationship shown below (CASQA 2003):

Where *volume* is specified in units of cubic-feet. Notice that the exponent is less than one, meaning that there are some economies of scale achieved with larger facilities. To better manage uncertainty associated with BMP placement and size, a standard unit centralized BMP was developed based on the analysis of some available existing centralized BMPs throughout the County. Figure 24 is a schematic of the unit-centralized BMP that was assumed for this study.

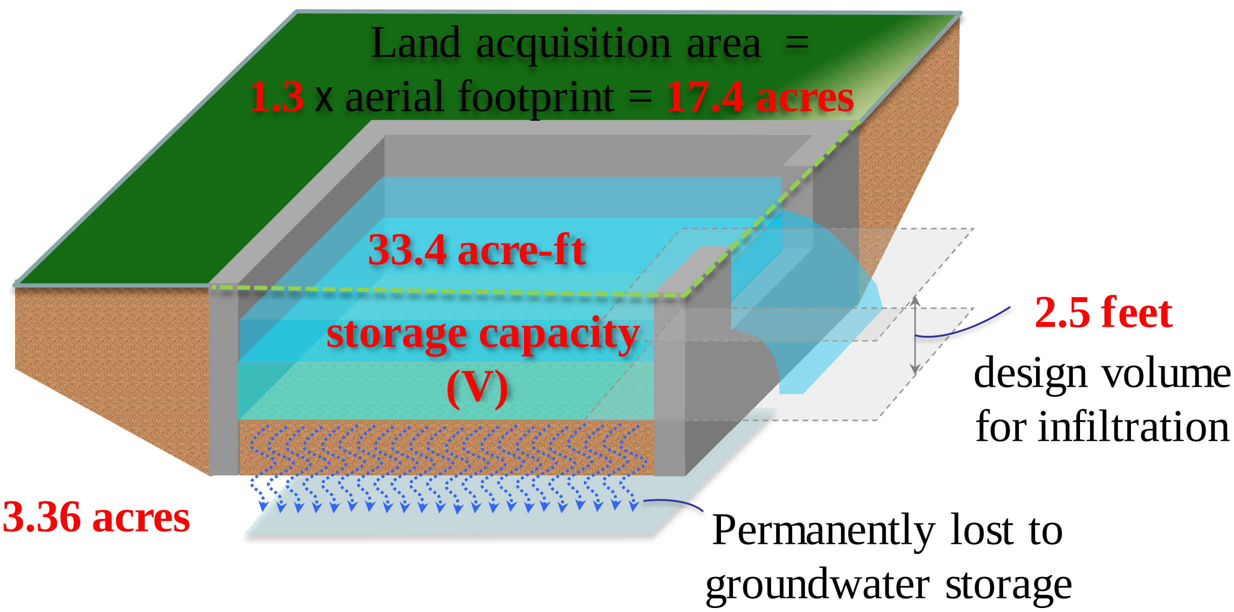

Figure 24. Unit-centralized BMP representation.

Maintenance costs for extended dry detention facilities are approximated to be about 4 percent of the initial capital cost per year (CASQA 2003). As a result, the present value (*PV*) of the maintenance cost over the life of the project is

where *n* is the number of years in the life of the project (assumed to be 20 years in this study) and *i* is the interest rate for inflation. Consistent with the distributed BMP cost estimates, an interest rate of 0.05 was used.

By using a unit-centralized BMP, nonlinearity was removed from the cost estimate. Instead of sizing and placing individual facilities, the required additional runoff capture volume for attainment could be represented by the number of unit-centralized BMPs. Considering the BMP configuration shown in Figure 24, land acquisition cost is calculated as $2.55 million x 17.4 acres = $44.3 million. BMP construction cost is calculated as $12.4 million x (33.4 acre-ft)$^{0.76}$ = $0.6 million. For maintenance costs, the present value of a twenty-year annualized cost using a 5 percent interest rate = 0.04 x $0.6 million x 12.462 = $0.3 million. Therefore, a lifecycle cost estimate of a unit-centralized BMP = $44.3 + $0.6 + $0.3 = $45.2 million. Because land acquisition cost represents over 98 percent of the total BMP cost and construction and maintenance cost represents 2 percent of total cost, the impact of any potential economies of scale realizable in the construction costs is minimal; therefore, using a standard unit-centralized BMP provides both a simple and meaningful estimator for centralized BMP cost.

Using the unit-centralized BMP cost and pollutant benefit relationships, an estimate of centralized BMP requirement needed to achieve attainment at each Degree of Practice was performed. This hypothetical scenario could have some practical application considering that centralized BMPs are facilities what would be constructed and maintained by public agencies on land acquired by public agencies. On the other hand, while distributed BMPs represent a cost-effective alternative, they rely on private property owners to take responsibility for proper operation and maintenance. Figure 25 shows the attainment cost for centralized BMPs under the baseline modeled condition for each Degree of Practice. Table 8 shows the marginal cost of implementation, computed as billion dollars per 1 percent increase in wet weather attainment.

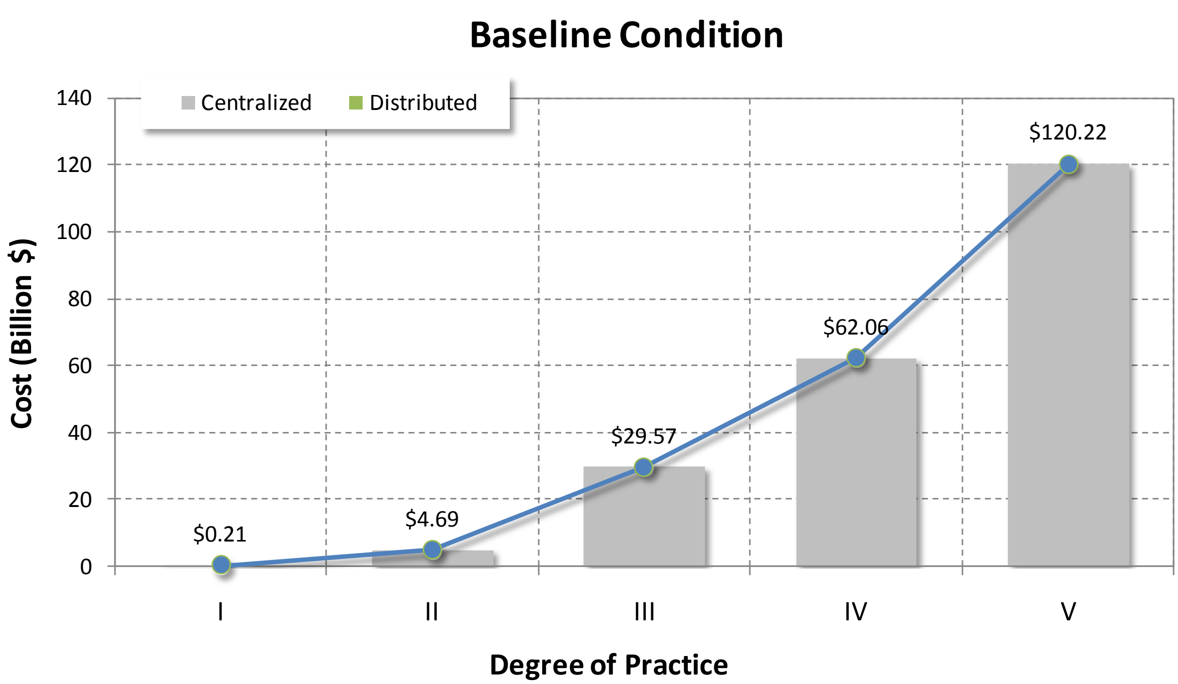

Figure 25. Attainment cost for centralized BMPs under baseline modeled condition versus Degree of Practice.

Table 8. Marginal cost of implementation for centralized BMP scenario

Degree of Practice (% attainment)	Cost ($ billion)	Marginal cost ($ billion / % attainment)
75	$0.21	0
85	$4.69	0.448
90	$29.37	4.936
95	$62.06	6.538
100	$120.22	11.632

With a $0.5 billion allowable threshold, Degree of Practice II (85 percent attainment) appears to be an appropriate inflection point for cost-effective implementation. Between Degrees of Practice I and II, each percentage point increase in attainment is achievable at a cost of about $0.5 billion. Above Degree of Practice II (85 percent attainment), the marginal cost increases to $5 billion, then to $6.5 billion above Degree of Practice III, and finally jumps to $11.6 billion for each percentage point increase between 95 percent and 100 percent attainment. Figure 26 shows attainment points above which centralized BMPs are needed in order to achieve 85 percent attainment at Degree of Practice II.

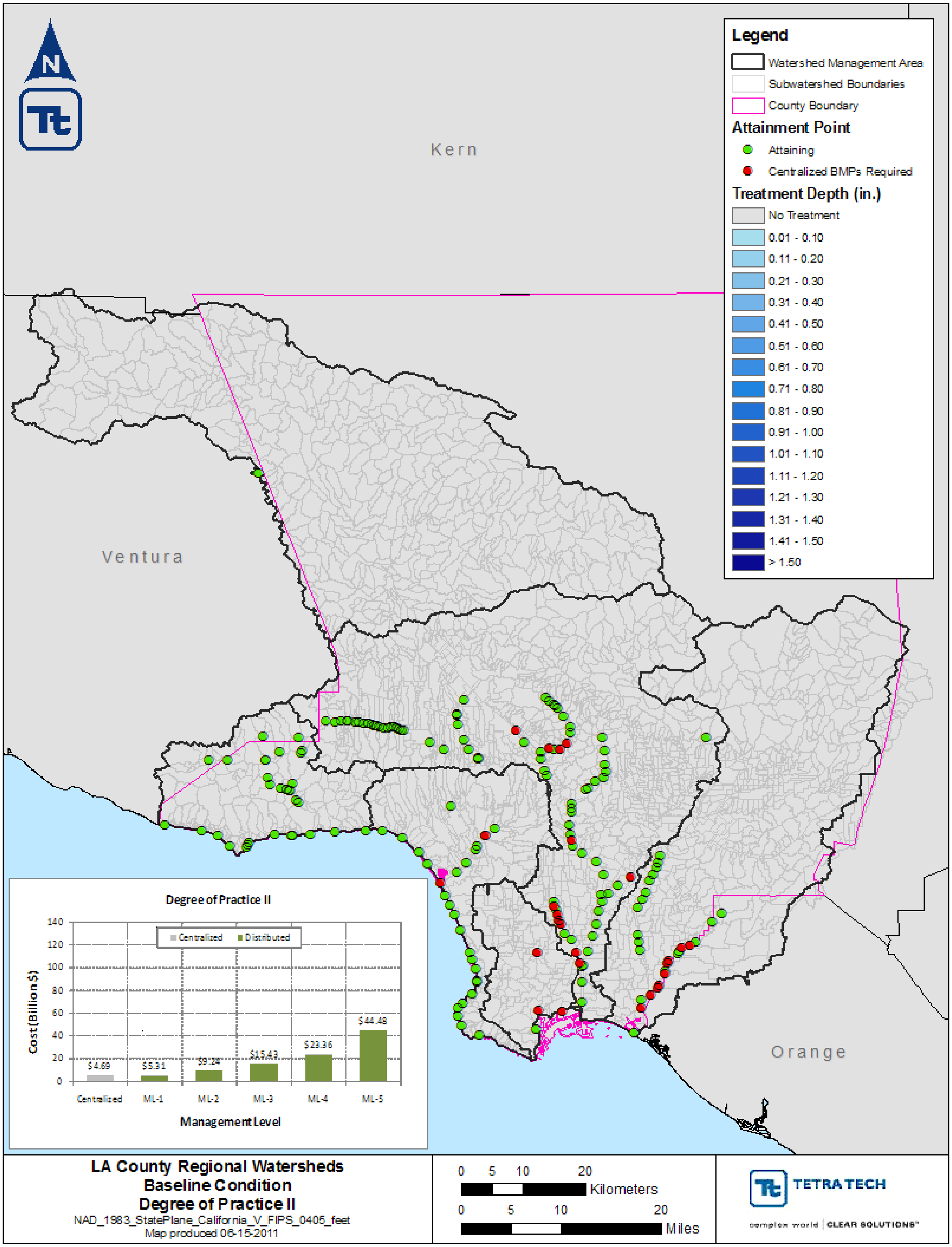

Figure 26. Baseline TMDL Attainment (with required centralized BMP locations) for Degree of Practice II.

5.3 Attainment Evaluation for Distributed BMPs plus Centralized

To test attainment sensitivity to management actions performed in the watershed, five proportional distributed BMP scenarios were modeled and evaluated for attainment at each of the five Degrees of Practice. These scenarios were configured assuming uniform application of each of the five Management Levels across all subwatersheds at each of the five Degrees of Practice, resulting in a total of 25 combinations. The centralized-only scenario provided an additional five reference points for comparison of these results.

For a given attainment point, if distributed BMPs were inadequate to achieve attainment at the specified Degree of Practice, centralized BMPs were applied to meet the attainment objective. Figure 27 shows the attainment cost distribution for uniform application of Management Level 1 (distributed BMPs) and the additional centralized BMP cost required for attainment at each Degree of Practice. For this scenario, every Degree of Practice requires additional centralized BMPs for attainment, with the highest three Degrees of Practice requiring significantly more than the lower two. Figure 28 is a similar graph, where uniform application of Management Level 5 is presented. This figure shows that uniform application of Management Level 5 is much more than necessary for attainment at Degrees of Practice I through III; however, at Degree of Practice IV (Figure 27 and Figure 28), Level 5 plus centralized is slightly cheaper than Level 1 plus centralized. Figure 29 and Figure 30 examine the search space from another perspective, where Degree of Practice is fixed at I and V, respectively, with uniform application of each Management Level for all subwatersheds.

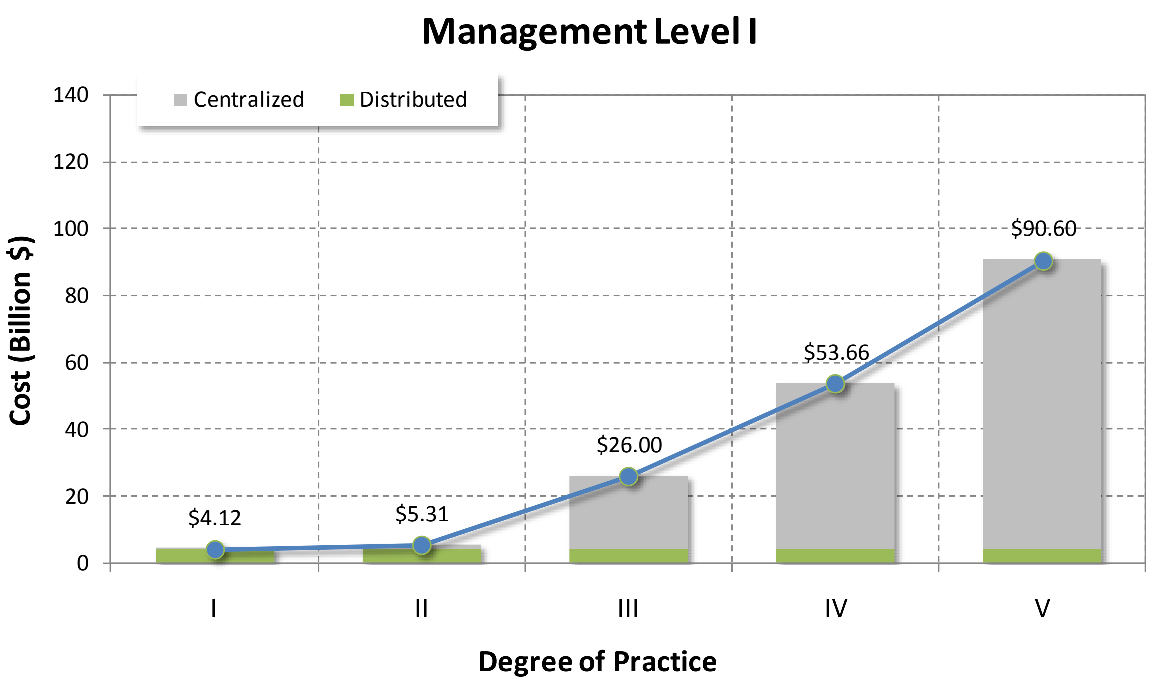

Figure 27. Attainment cost for uniform application of Management Level 1 with centralized BMPs versus Degree of Practice.

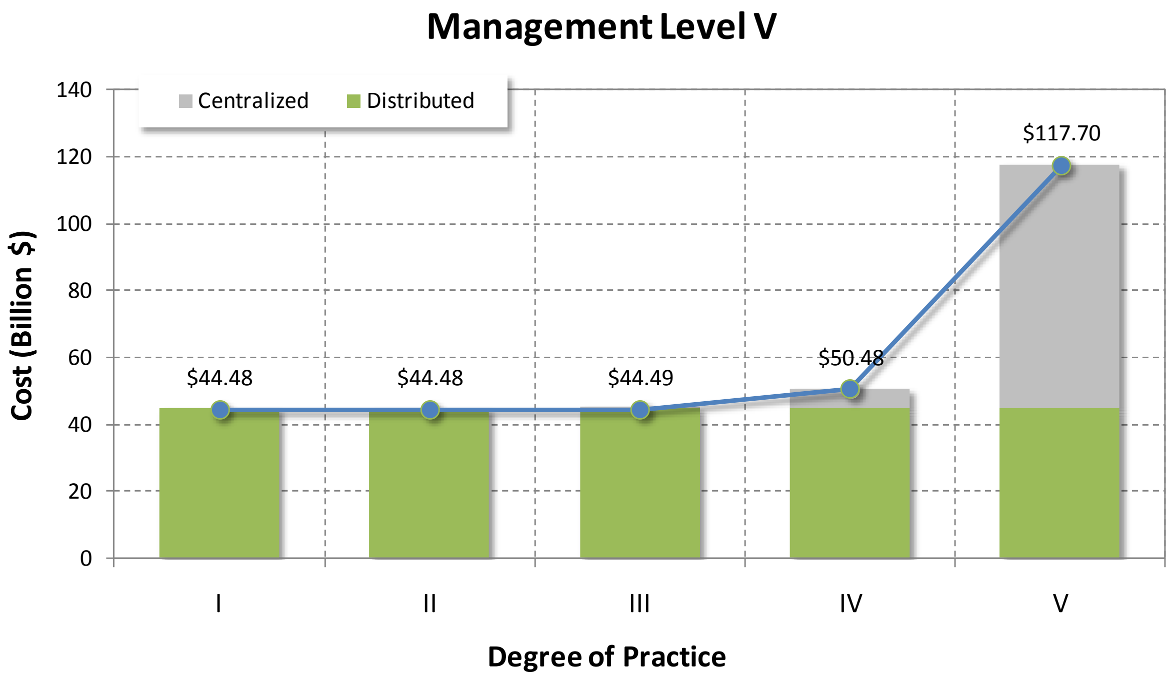

Figure 28. Attainment cost for uniform application of Management Level 5 with centralized BMPs versus Degree of Practice.

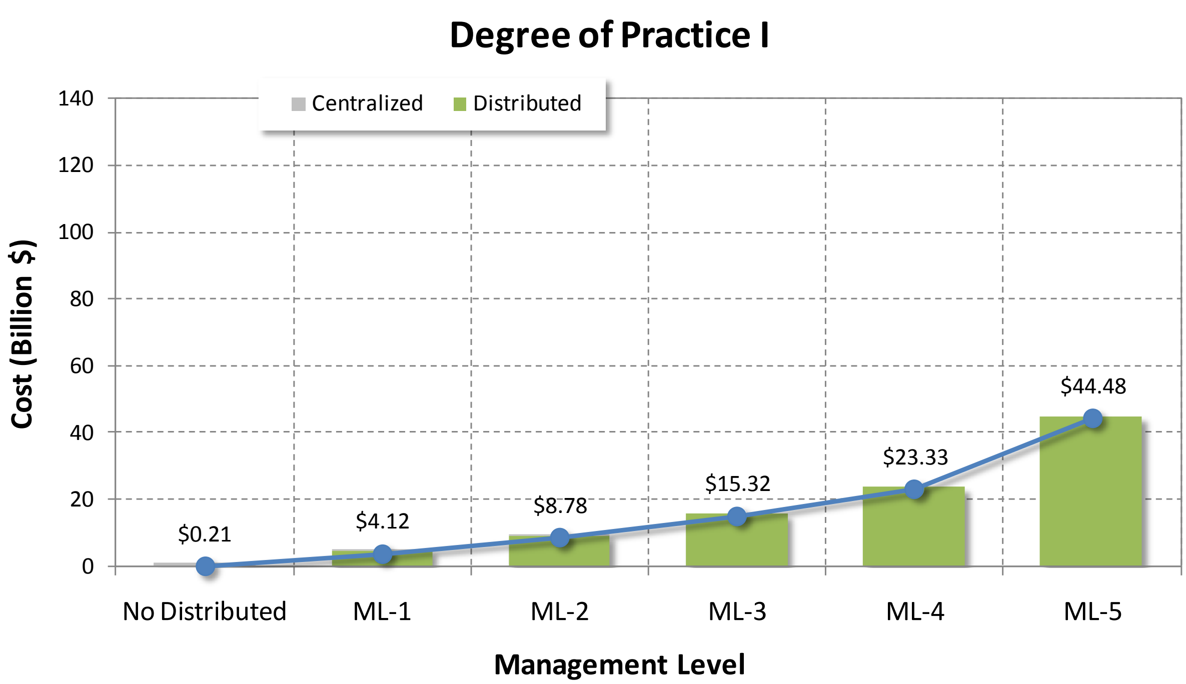

Figure 29. Attainment cost for uniform application of each Management Level with centralized BMPs for Degree of Practice I.

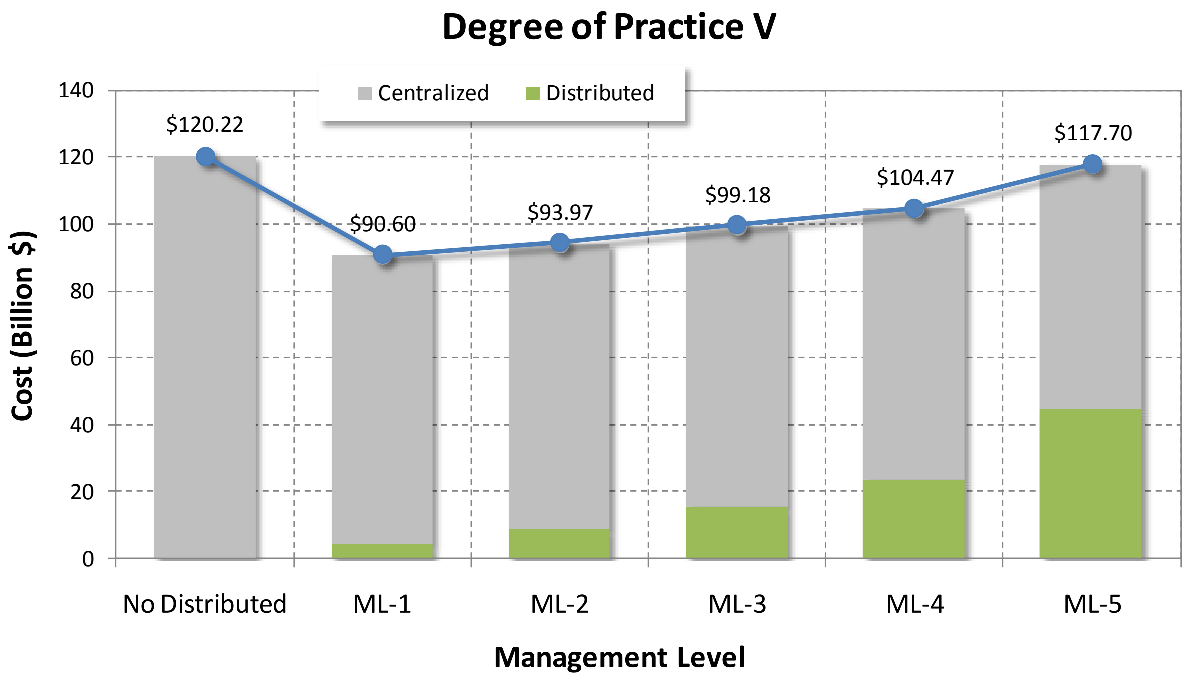

Figure 30. Attainment cost for uniform application of each Management Level with centralized BMPs for Degree of Practice V.

Figure 29 suggests that at Degree of Practice I (75 percent attainment), about five strategically placed centralized BMPs will likely achieve the attainment objective at a total cost of about $210 million. It also suggests that the lowest-level application of distributed BMPs is also more than adequate to achieve attainment at a relatively low cost. On the other hand, at the other extreme end of the spectrum, Figure 30 suggests that if 100 percent attainment is the goal, it is more cost-effective to focus nearly exclusively on centralized BMPs (gray infrastructure) and minimize distributed BMPs (green infrastructure). It also suggests, however, that distributed BMP implementation opportunity should not be entirely ignored. Note the dramatic cost savings associated with even the lowest-level adoption of distributed BMPs. Moving from no distributed BMPS to adoption of uniform Management Level 1 plus centralized BMPs reduces the centralized BMP burden by nearly $30 billion. Between the four extremes presented in Figure 27 through Figure 30 are a range of opportunities that define the upper plane of the optimization search space. Figure 31 is a three-dimensional rendering of total attainment cost for uniform application of distributed and centralized BMPs by both Management Level and Degree of Practice on the perpendicular axis. The cost distribution associated with the edges of this plane corresponds to Figure 27 through Figure 30.

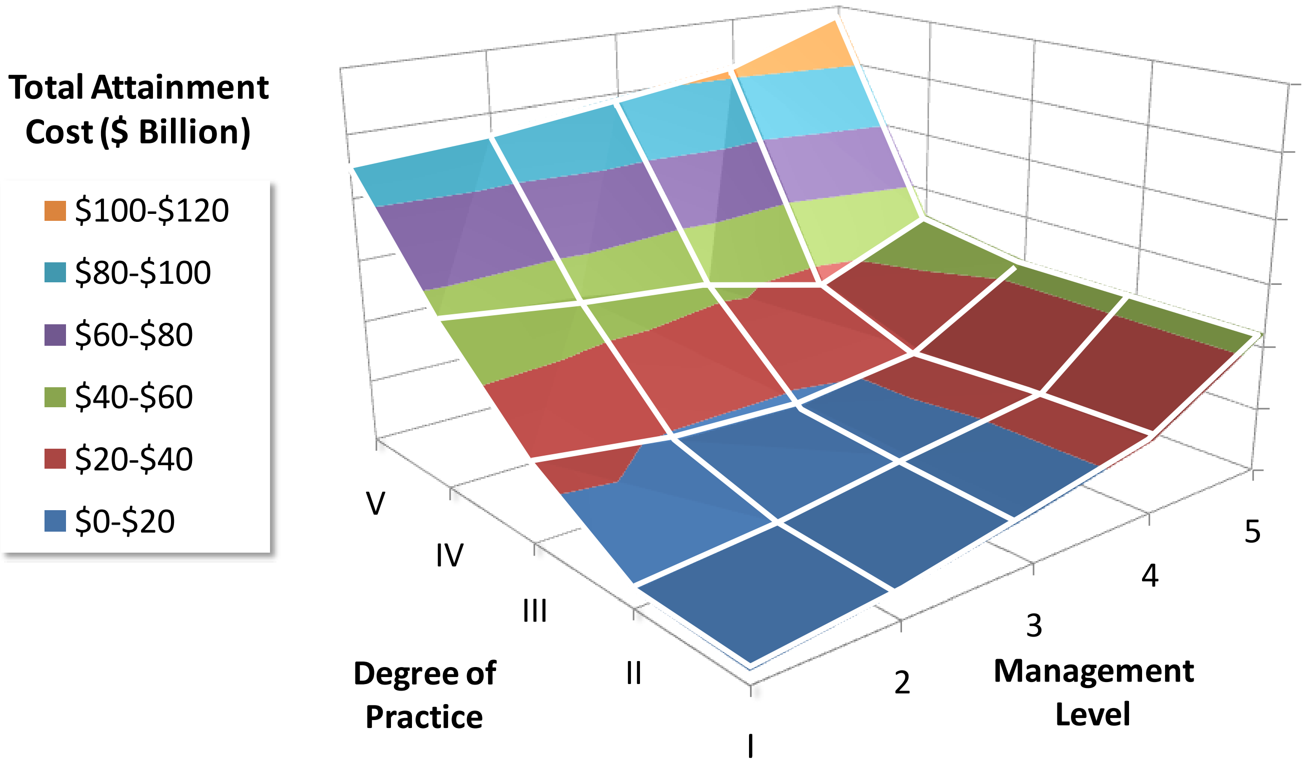

Figure 31. Total attainment cost for uniform application of distributed and centralized BMPs by Management Levels and Degrees of Practice.

In two-dimensional space, the “knee of the curve” is typically used to identify the most cost-effective point in the search space above which marginal cost increases dramatically. Because we are measuring cost-effectiveness as a function of two variables that form a cost-effectiveness plane instead of a curve, the “bowl of the plane” is conceptual counter-part to the “knee of the curve.” This depression is most easily identified by calculating the cost-effectiveness associated with each of the 25 points that define the plane. Zinc is the limiting pollutant in most cases, so it was used as an example for this calculation. Figure 32 shows the zinc load reduction required for attainment by Management Levels and Degrees of Practice. Figure 33 shows the cost-effectiveness for zinc load reduction for attainment by Management Levels and Degrees of Practice. This cost-effectiveness plane (or marginal cost plane) shown in Figure 33 was calculated by dividing the cost plane in Figure 31 by the attainment load reduction plane in Figure 32.

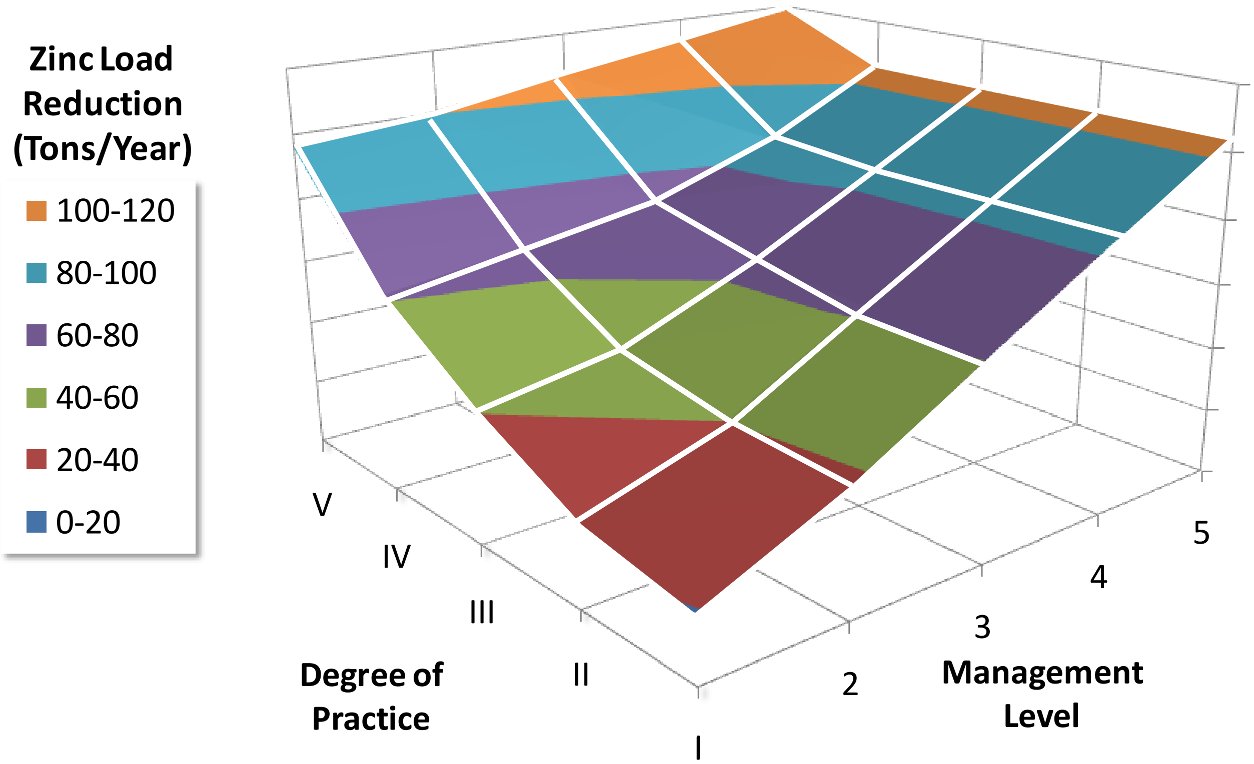

Figure 32. Total zinc load reduction needed for attainment by Management Levels and Degrees of Practice.

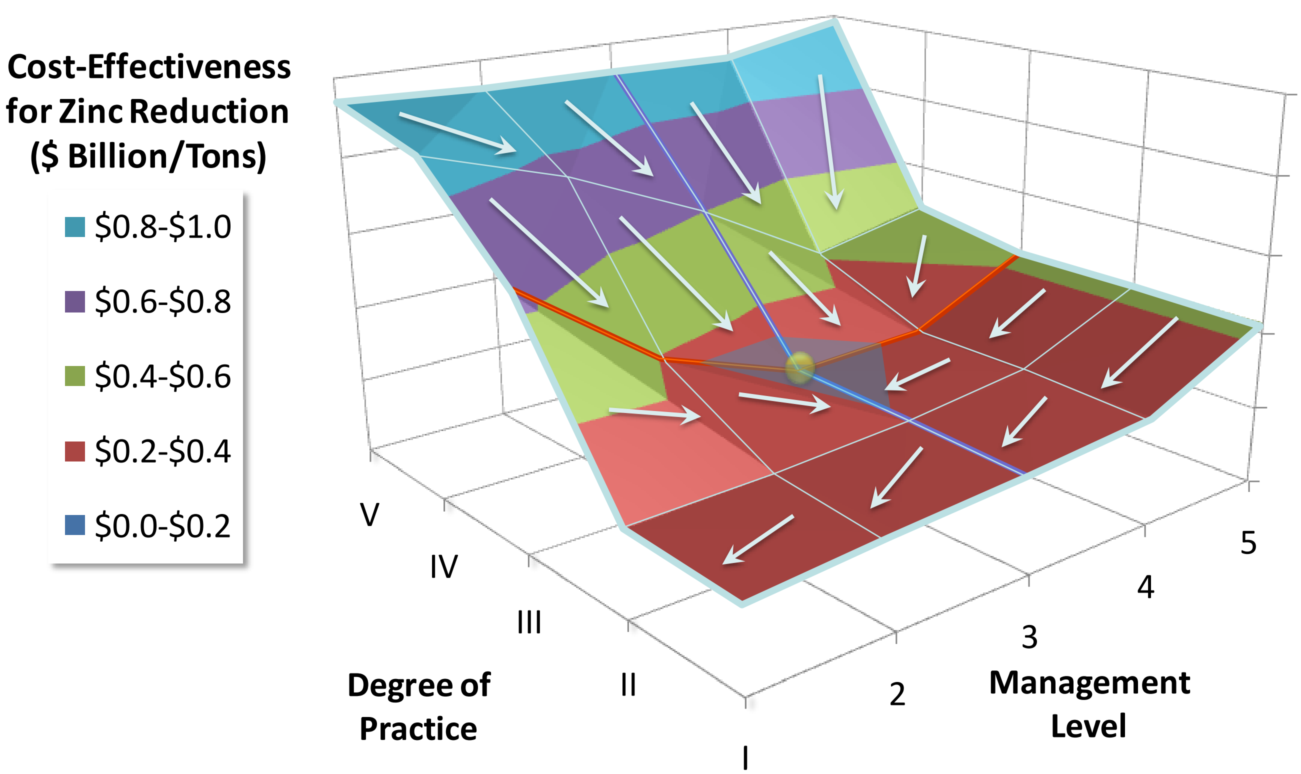

Figure 33. Cost-effectiveness for zinc load reduction by Management Levels and Degrees of Practice.

The analysis suggests a natural depression in the cost-effectiveness plane (defined by the lowest cost for the highest reduction benefit by Management Level and Degree of Practice) exists at Degree of Practice III and Management Level 3. Figure 34, which highlights the Management Level 3 and Degree of Practice III transects of the zinc cost-effectiveness plane shown in Figure 33, helps to visualize the shape of the depression at this point in the search space.

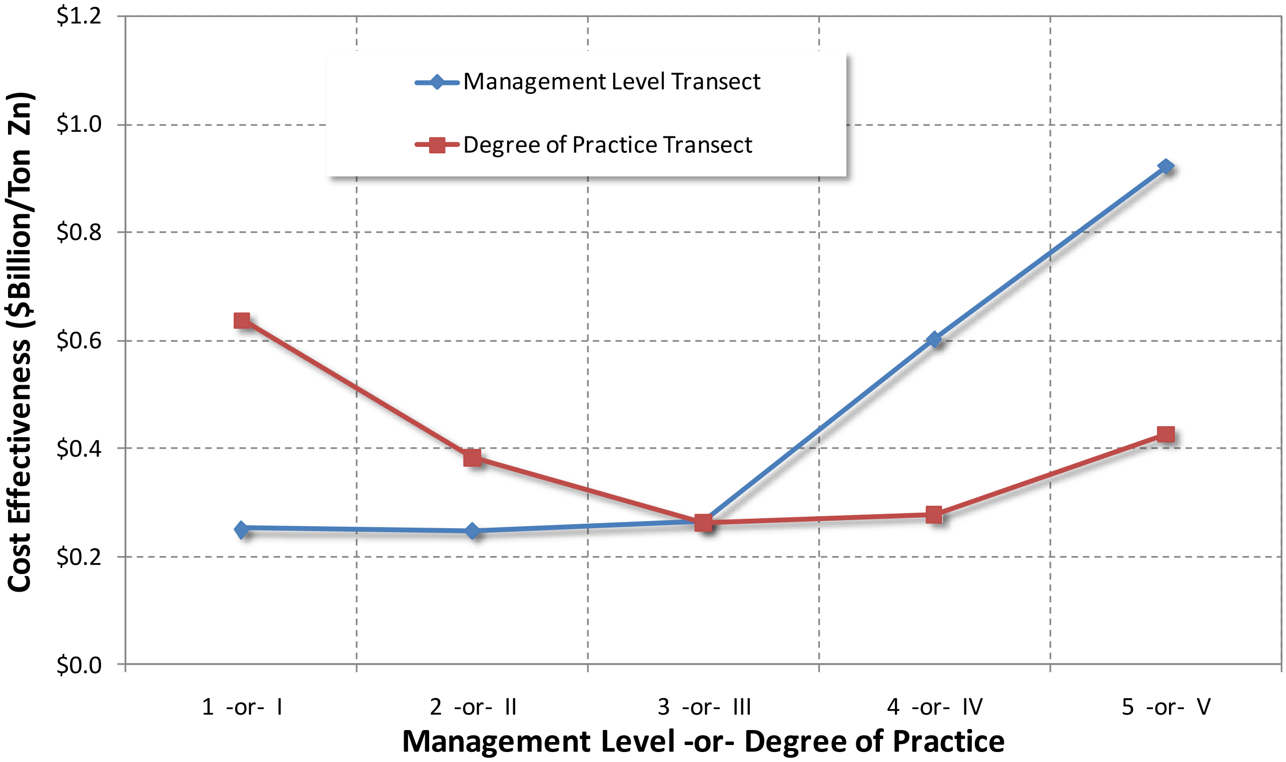

Figure 34. Management Level 3 and Degree of Practice III transects on the zinc cost-effectiveness plane.

Figure 35 shows the total attainment cost distribution for uniform application of Management Level 3 with centralized BMPs versus Degree of Practice, while Figure 36 shows attainment cost distribution for the centralized-only scenario beside uniform application of each of the five distributed BMP Management Levels, with centralized BMPs making up the difference for attainment at Degree of Practice III (90 percent attainment). In each graph, Degree of Practice III with Management Level 3 is at the very center of the search plane. This is the inflection point that provides the highest achievable Degree of Practice (90 percent attainment), maximizes the use of distributed BMPs (uniform application of Management Level 3), and minimizes the reliance on the relatively more costly centralized BMPs. (Centralized BMPs represent less than 10 percent of the total attainment cost.) Because centralized BMPs generally represent the highest source of modeled uncertainty in terms of selection, placement, and expected performance, minimizing their use is also one objective of the selection of an optimal point within the search space.

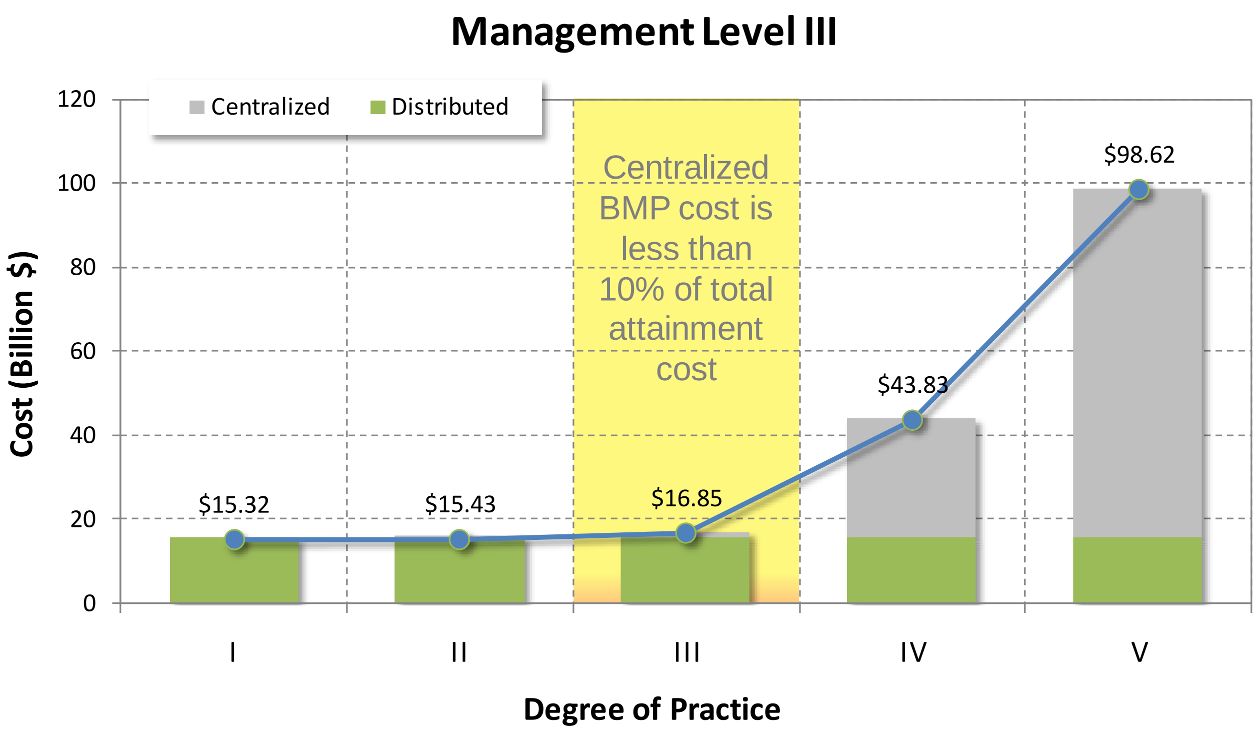

Figure 35. Attainment cost for uniform application of Management Level 3 with centralized BMPs versus Degree of Practice.

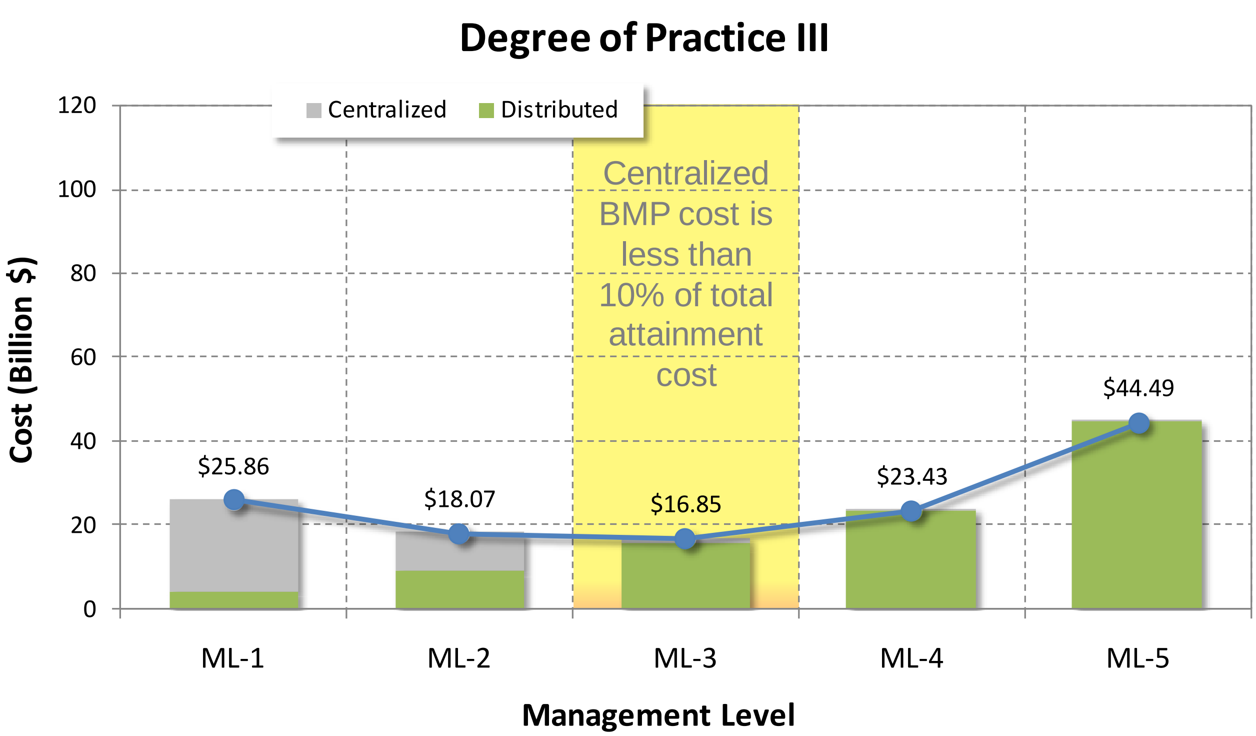

Figure 36. Attainment cost for uniform application of each Management Level with centralized BMPs for Degree of Practice III (90% attainment).

There are less costly options available within the search space; however, it is recognized that they also exist at a lower Degree of Practice. For example, consider the transect associated with Degree of Practice II. This the inflection point previously identified during the centralized BMP-only analysis. Figure 37 shows attainment cost distribution for the centralized-only scenario beside uniform application of each of the five distributed BMP Management Levels, with centralized BMPs making up the difference for attainment at Degree of Practice II (85 percent attainment). This graph suggests that if Degree of Practice II is selected as an acceptable attainment target, the lowest total implementation cost is achievable with only centralized BMP application.

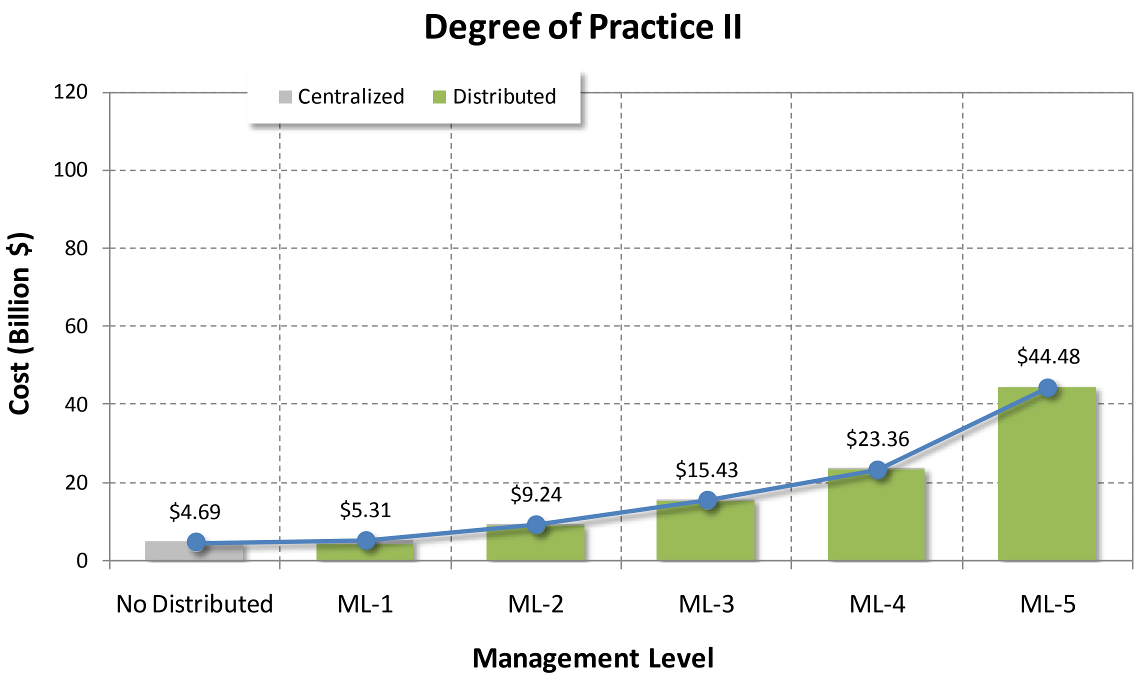

Figure 37. Attainment cost for uniform application of each Management Level with centralized BMPs for Degree of Practice II (85% attainment).

5.4 Spatial Evaluation of Distributed BMPs plus Centralized BMP attainment

As presented and described above, the uniform Management Level implementation scenarios provide a reference point for evaluating potential cost-saving solutions that may be identified through large-scale watershed optimization. They also provide insight into the range of response and expected outcomes that can be achieved through stormwater management. Figure 38 through Figure 42 are maps that show treatment capacity versus wet-weather attainment for Degree of Practice III (90 percent wet-weather attainment). Figure 43 illustrates attainment for Management Level V implementation for Degree of Practice V (100 percent wet-weather attainment). Each of these maps also has three distinctive ways in which data are presented. First, at any given Management Level, the treatment capacity depth for each subwatershed was computed as the collective storage volume of all management practices (i.e. available storage depth plus media void space), divided by the total treatable impervious area within that subwatershed. Converting treatment capacity (originally a volume) to a depth basis provides a surrogate indicator of the storm size that can be completely contained and treated within that subwatershed under dry antecedent conditions. Second, the in-stream attainment condition was presented using a red dot for nonattainment of at least one standard and a green dot for attainment for all applicable standards. The red attainment points highlight the locations that require additional centralized BMPs. Third, each figure contains a bar graph highlighting the total implementation cost associated with the collective set of management actions at the watershed scale required to achieve the displayed attainment spatial distribution.

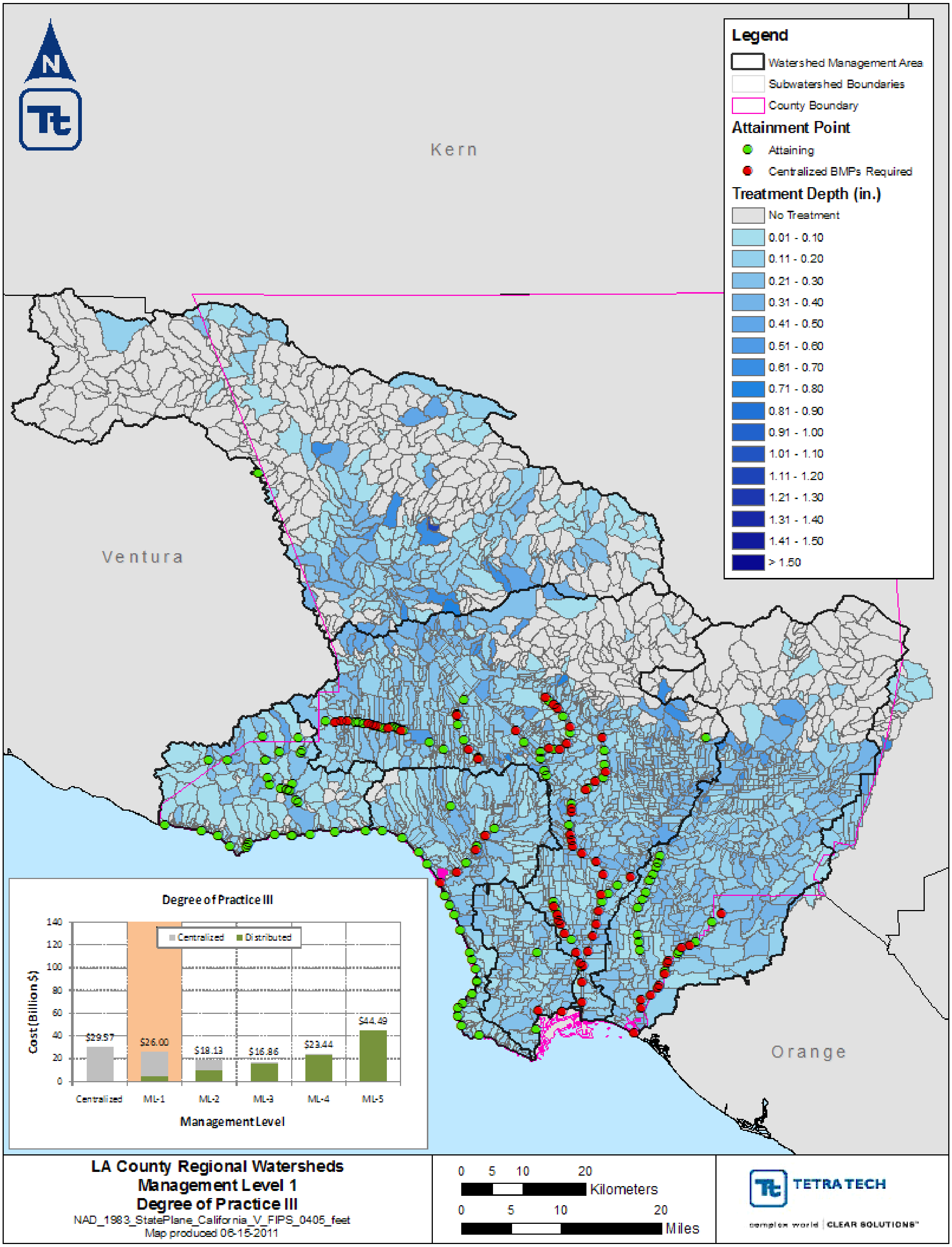

Figure 38. Management Level I vs. TMDL attainment at Degree of Practice III (90% wet-weather attainment).

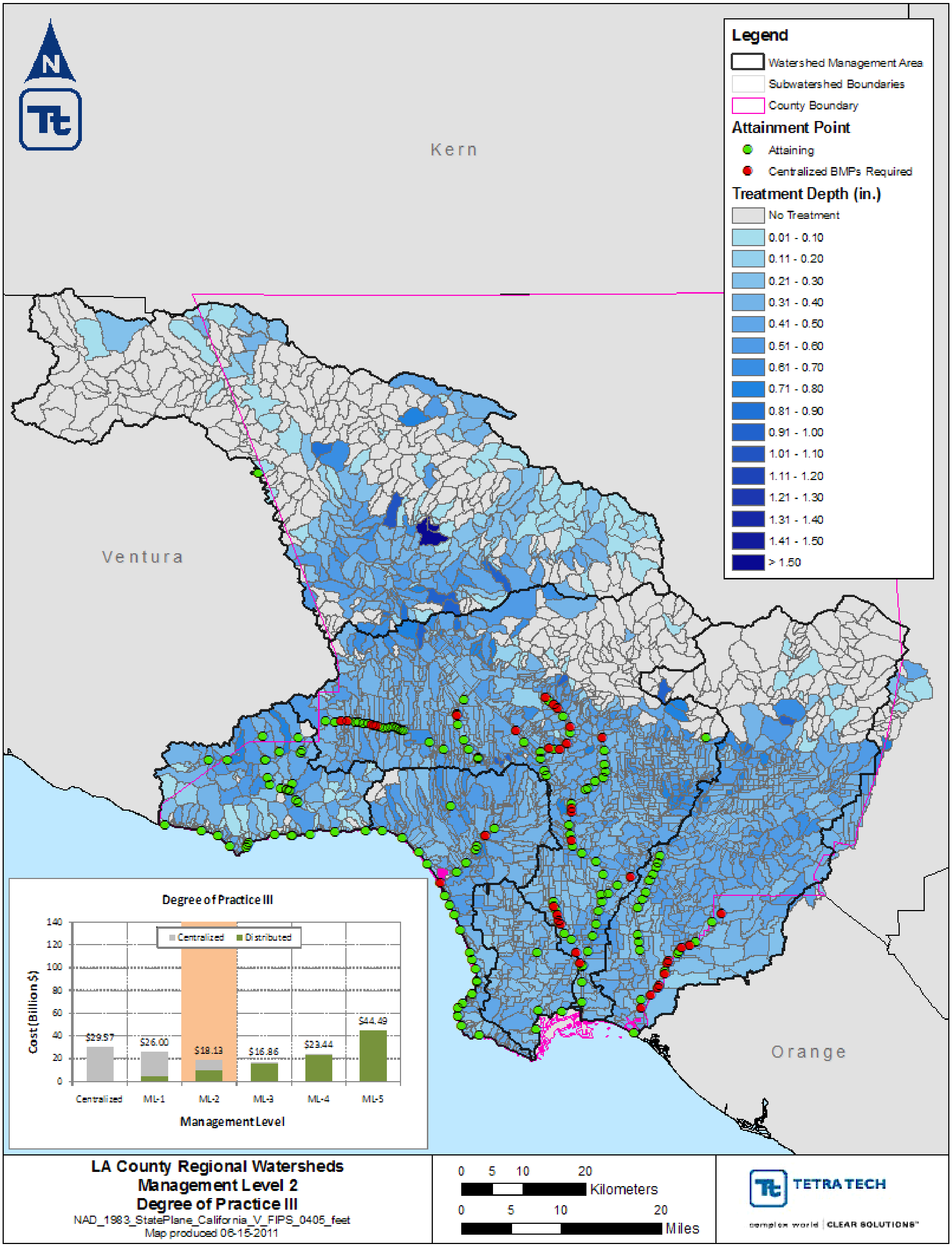

Figure 39. Management Level II vs. TMDL attainment at Degree of Practice III (90% wet-weather attainment).

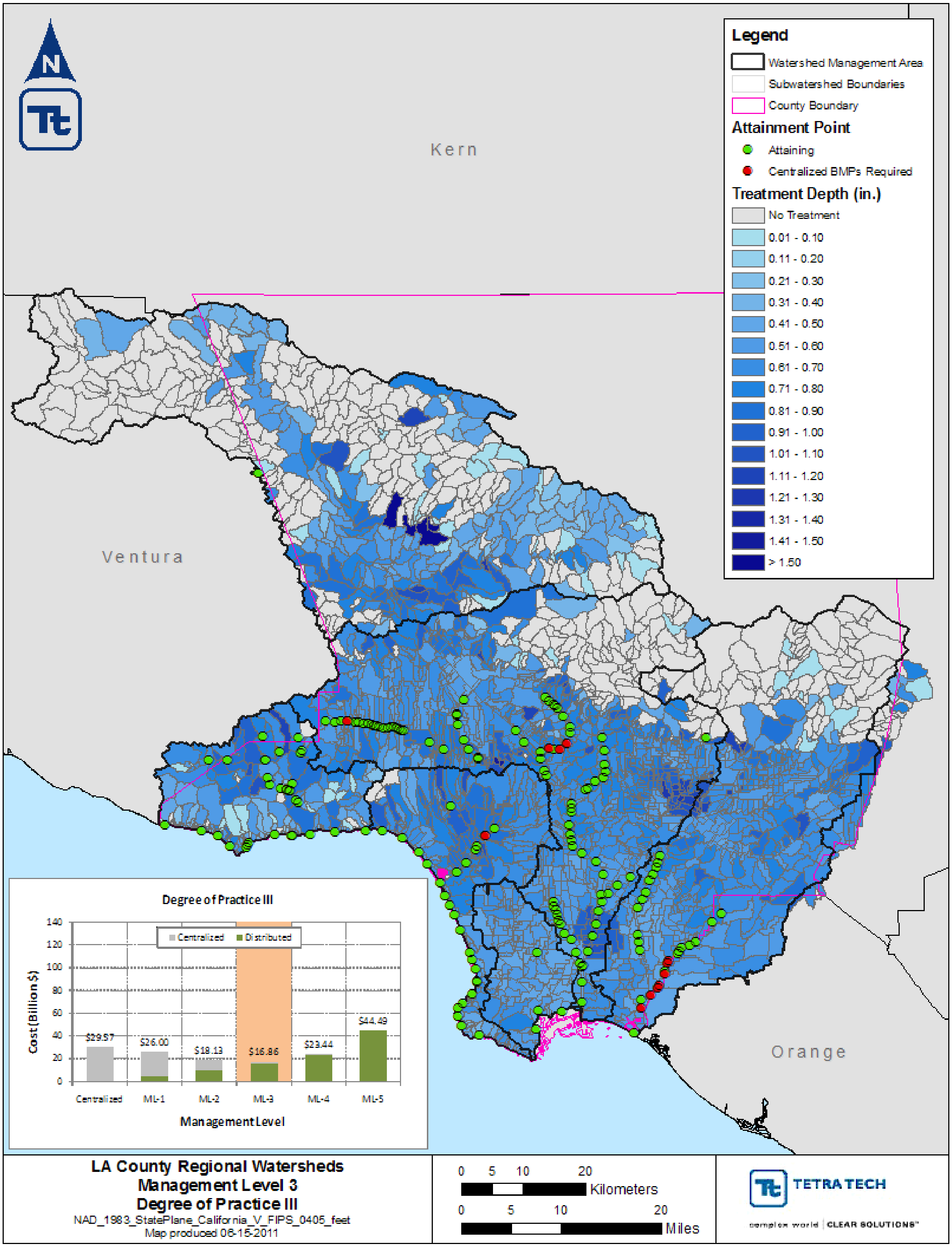

Figure 40. Management Level III vs. TMDL attainment at Degree of Practice III (90% wet-weather attainment).

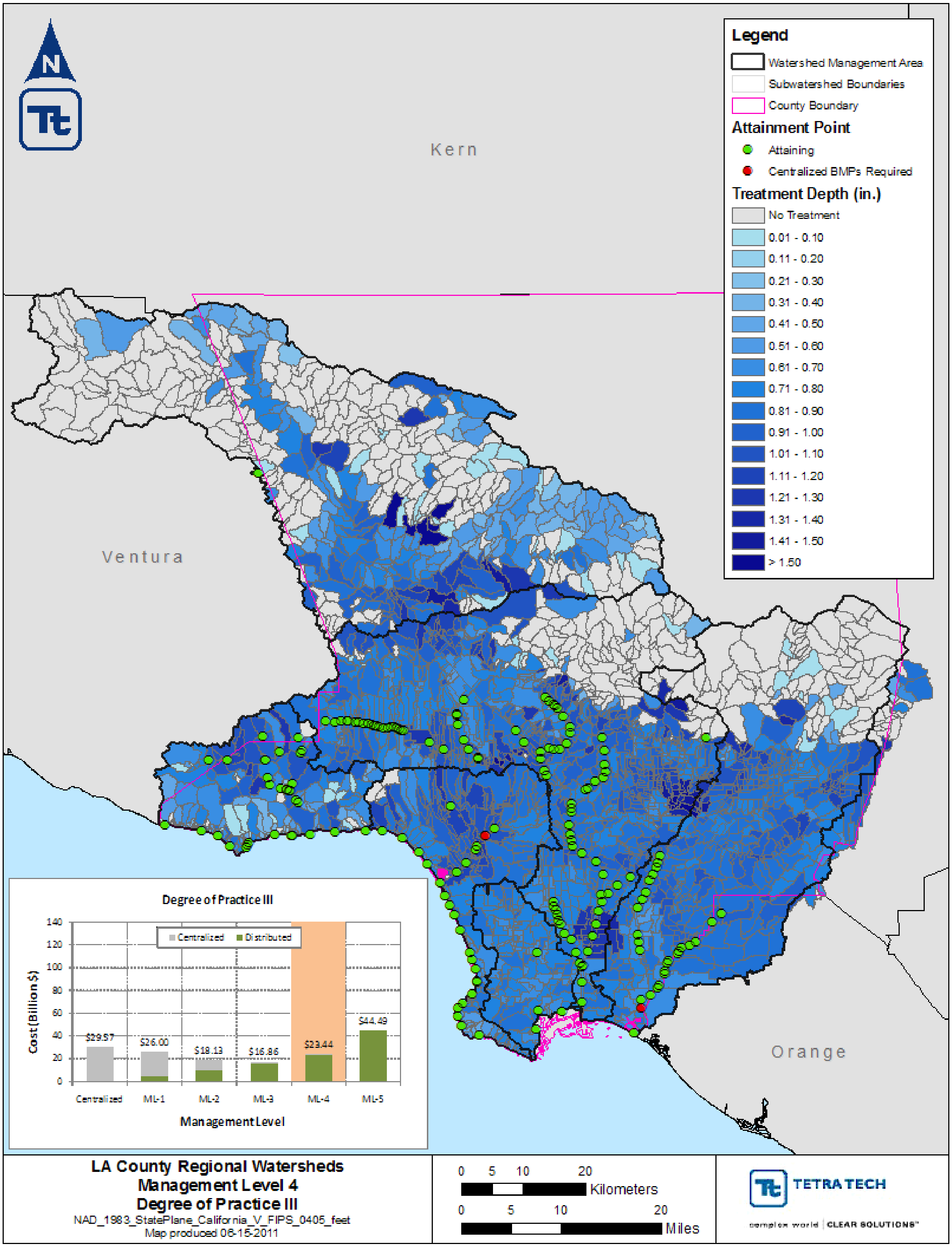

Figure 41. Management Level IV vs. TMDL attainment at Degree of Practice III (90% wet-weather attainment).

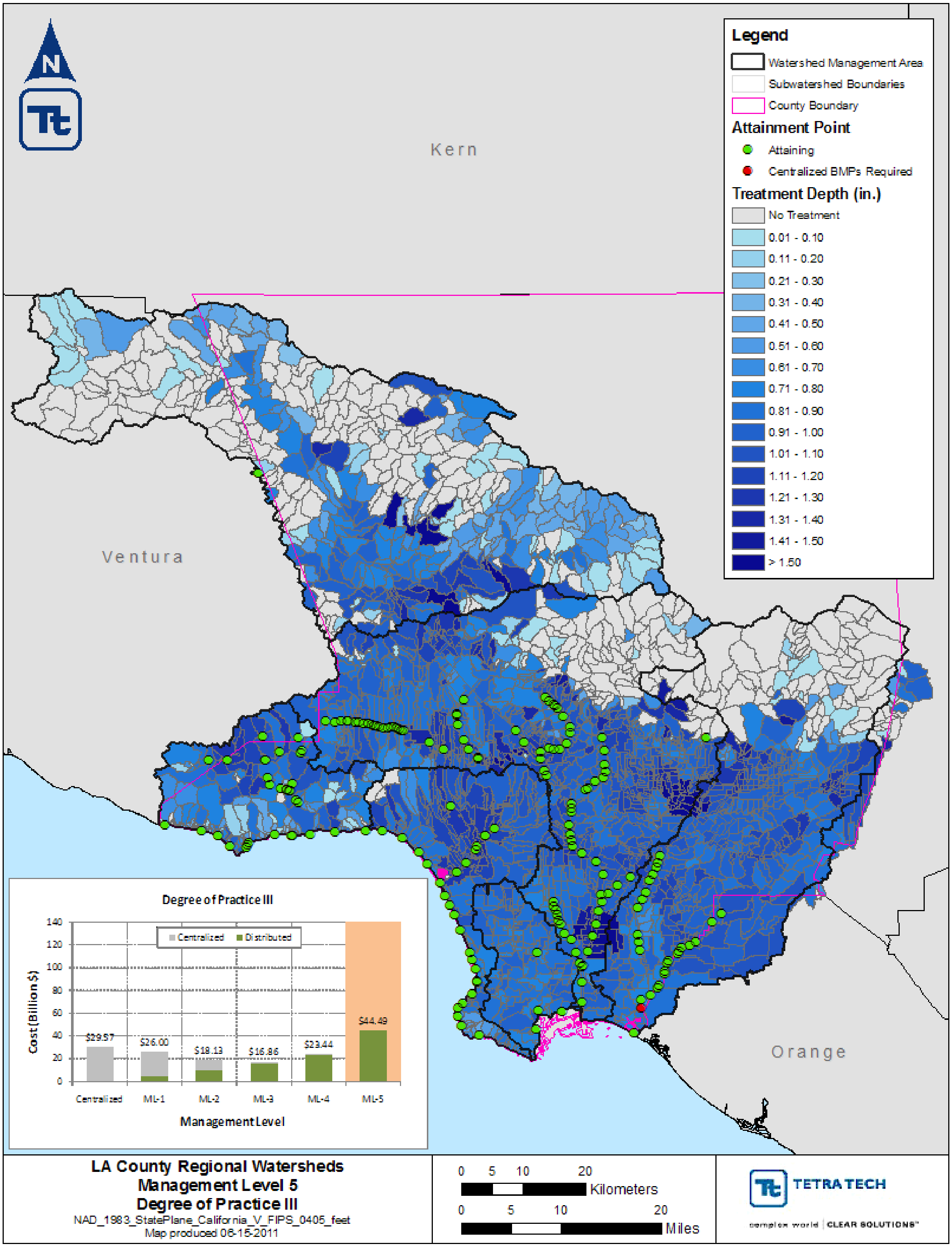

Figure 42. Management Level V vs. TMDL attainment at Degree of Practice III (90% wet-weather attainment).

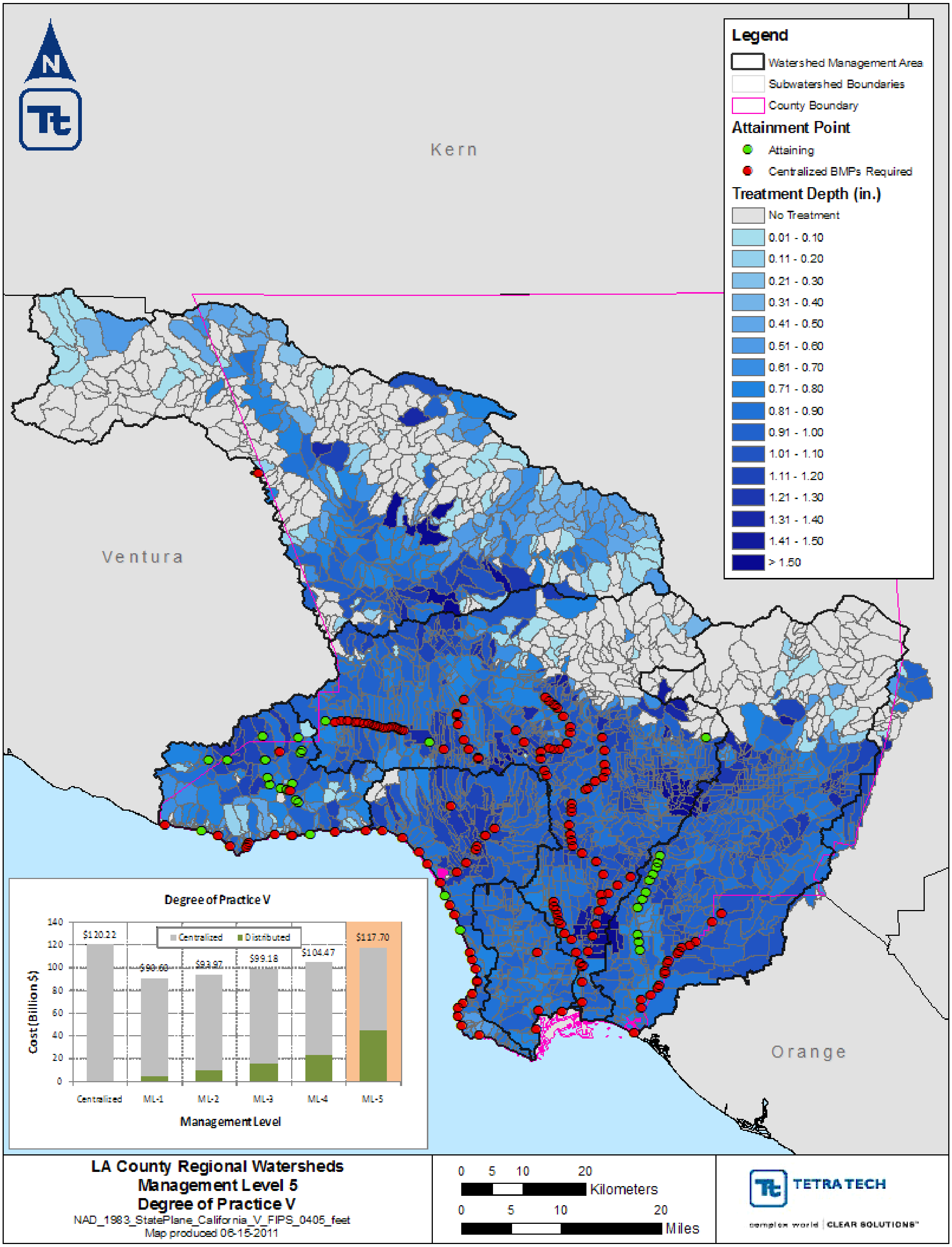

Figure 43. Management Level V vs. TMDL attainment at Degree of Practice V (100% wet-weather attainment).

5.5 Fecal Coliform Reduction Evaluation

Because of the relatively high number of exceedance days and the magnitude of exceedance associated with fecal coliform, in-stream fecal coliform attainment was not enforced as a constraint for this analysis. Nonetheless, because fecal coliform is still being modeled, it is possible to show the ancillary reduction benefit that results from managing other pollutants. Unit area loads (number per acre) were also calculated for fecal coliform to show the benefit at each Management Level. These results were normalized to the baseline unit area load, expressing the load reductions as a percentage of the baseline condition. Figure 44 shows the results of this analysis for Management Levels I–V at the outlet of subwatershed 1007 (at the mouth of Ballona Creek). This location was chosen for demonstration purposes because it is an optimization attainment point that is also listed for fecal coliform. The analysis suggests that managing the entire Ballona Creek watershed at Level V would result is a 61 percent load reduction for fecal coliform relative to baseline.

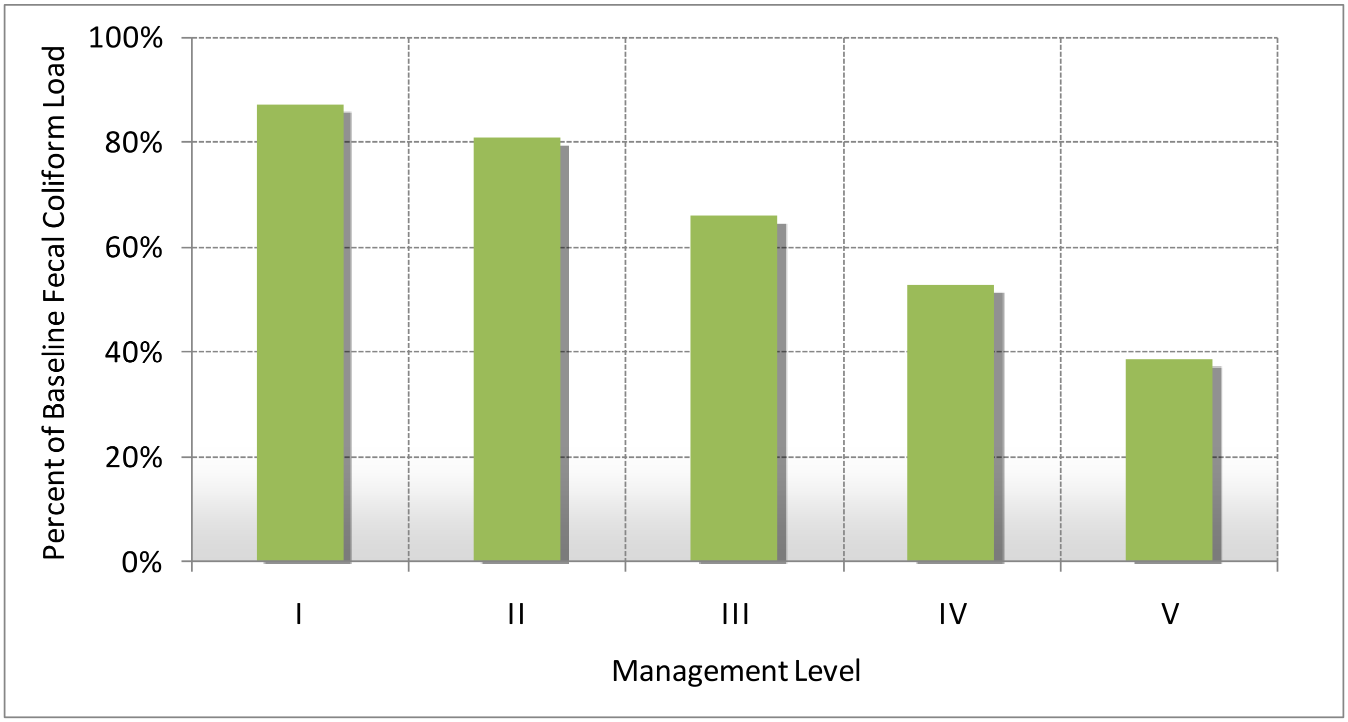

Figure 44. Fecal coliform wet-weather load reduction at the outlet of Ballona Creek.

Although this treatment shows relatively large load reductions, the reductions do not translate into comparably large reductions in wet-weather exceedance days. To quantify the relationship between Management Level reductions and wet-weather exceedances, fecal coliform concentration time series data were ranked by magnitude to generate concentration-exceedance curves for the baseline condition and for each Management Level. Each of these curves was then plotted against the 400 #/100mL fecal coliform standard. The concentration-exceedance curve for subwatershed 1007 is presented below as Figure 45. The point where the standard line crosses the exceedance curve indicates the exceedance frequency for the corresponding management level. There is only an 11 percent absolute difference in exceedance frequency between baseline (81 percent) and Level 5 (70 percent), even though Figure 44 shows a 61 percent reduction.

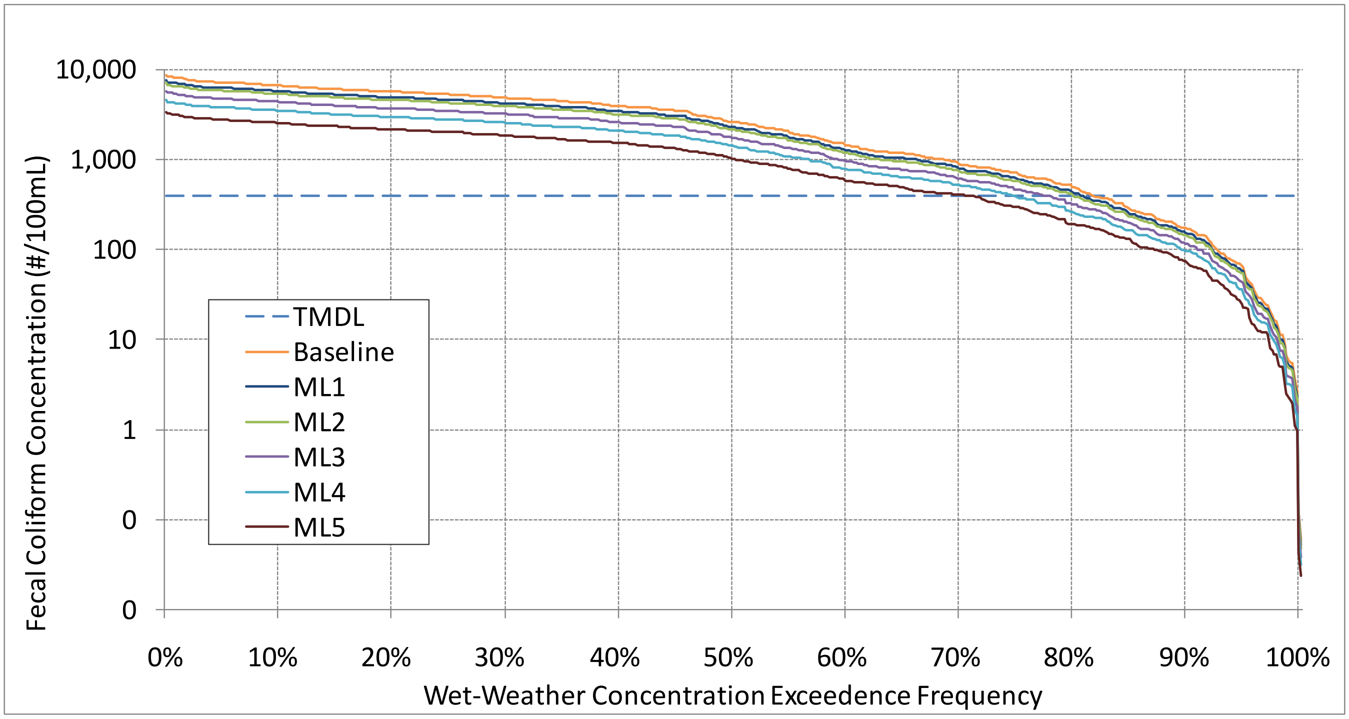

Figure 45. Fecal coliform concentration-exceedance curve for subwatershed 1007.

Figure 46 through Figure 50 are maps that show the percent reduction in unit area loads for fecal coliform, relative to baseline conditions, for Management Levels 1 through 5 for all urban watersheds in Los Angeles County. Wet-weather exceedances of the 400 #/100mL standard are presented at in-stream attainment points using dots on a red-to-yellow scale, where red indicates higher exceedance frequency and yellow indicates lower. The maps highlight a strong correlation between increasing Management Level and decreasing unit area loads of fecal coliform. Consistent with what was observed in Figure 45 for Ballona Creek, the relatively large load reduction does not translate into comparably large reductions in wet-weather exceedances. Figure 50 (Management Level 5) shows greatly reduced loads; however, a large number of attainment points still show wet-weather exceedances higher than 70 percent.

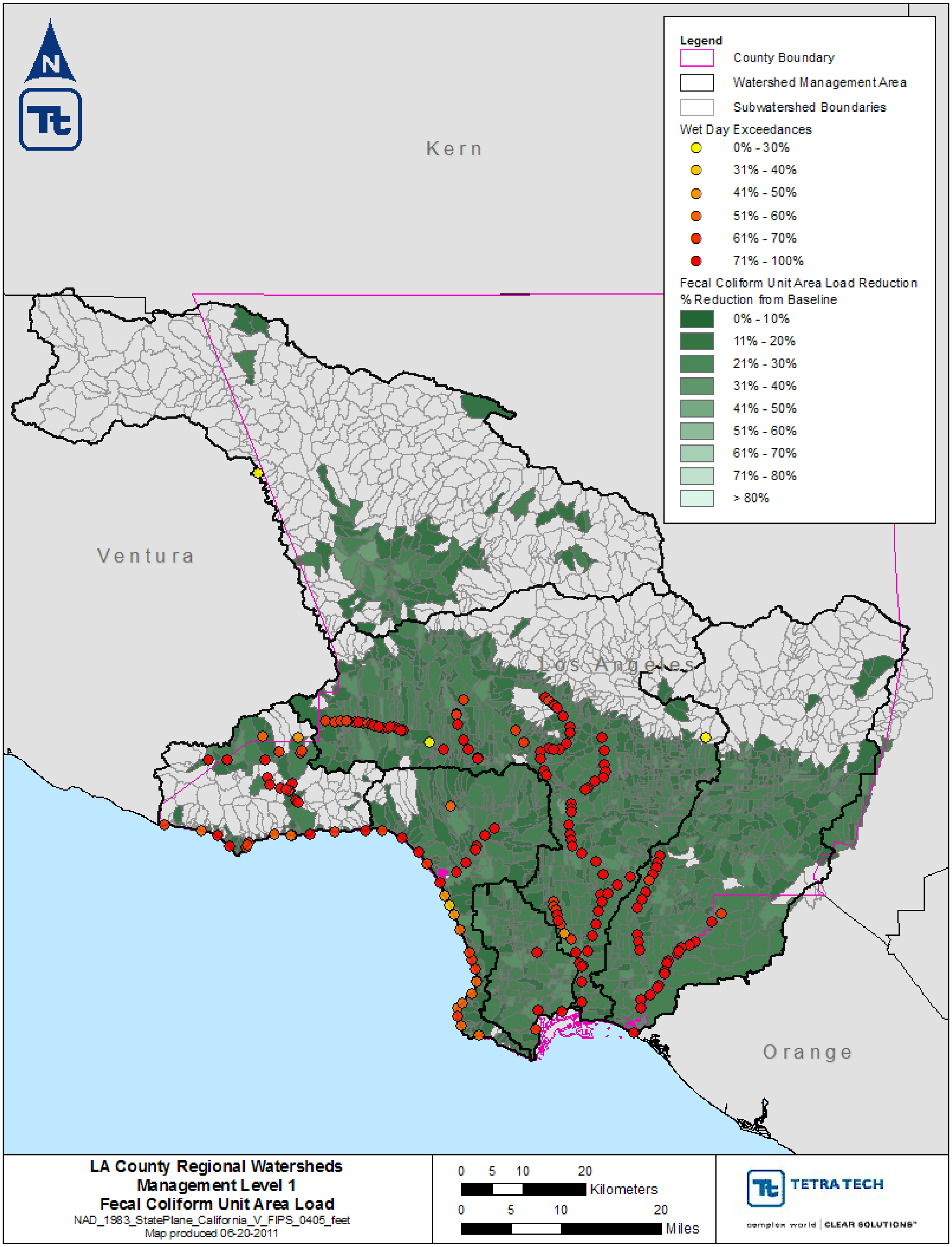

Figure 46. Management Level I fecal coliform unit area load reduction (% from baseline).

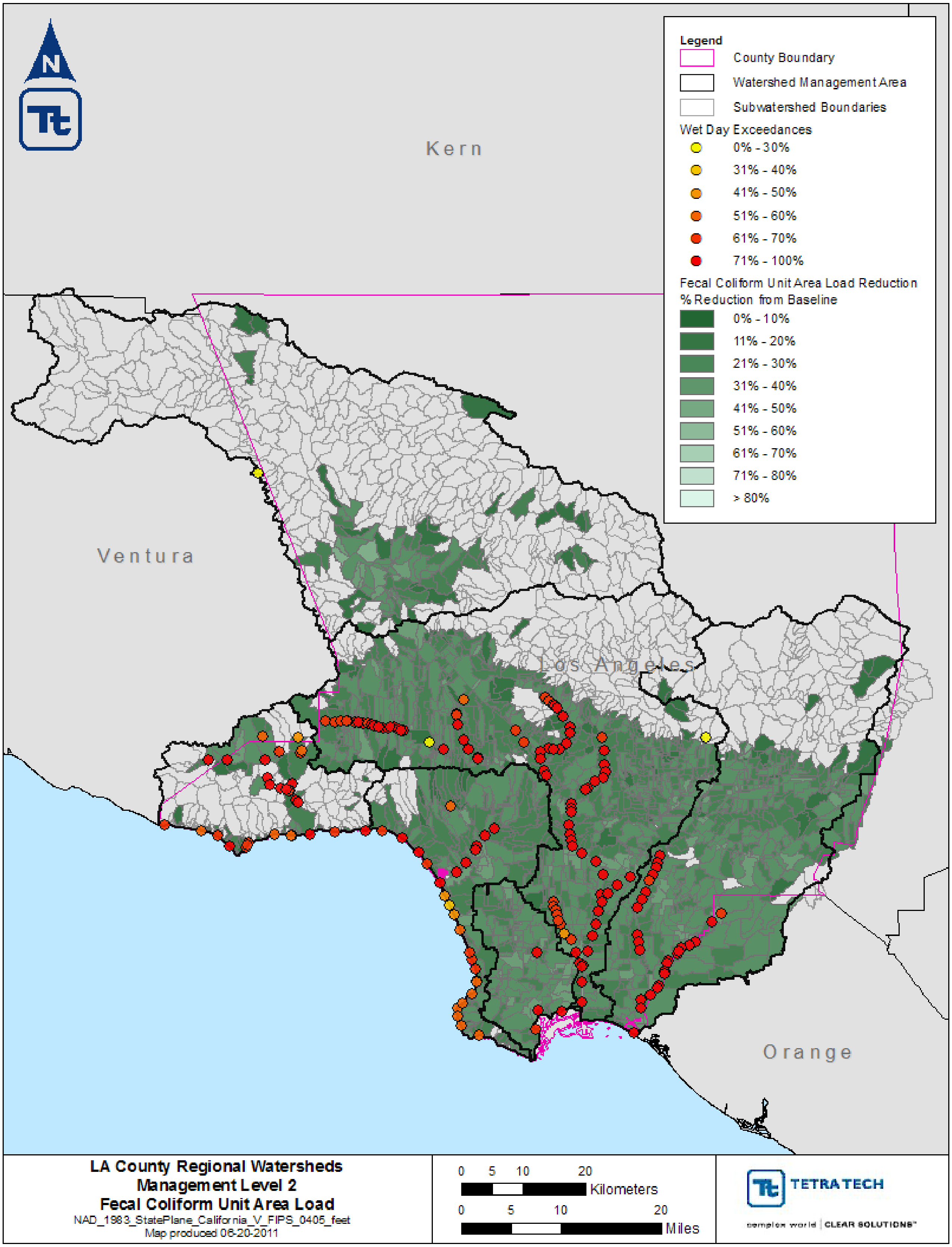

Figure 47. Management Level II fecal coliform unit area load reduction (% from baseline).

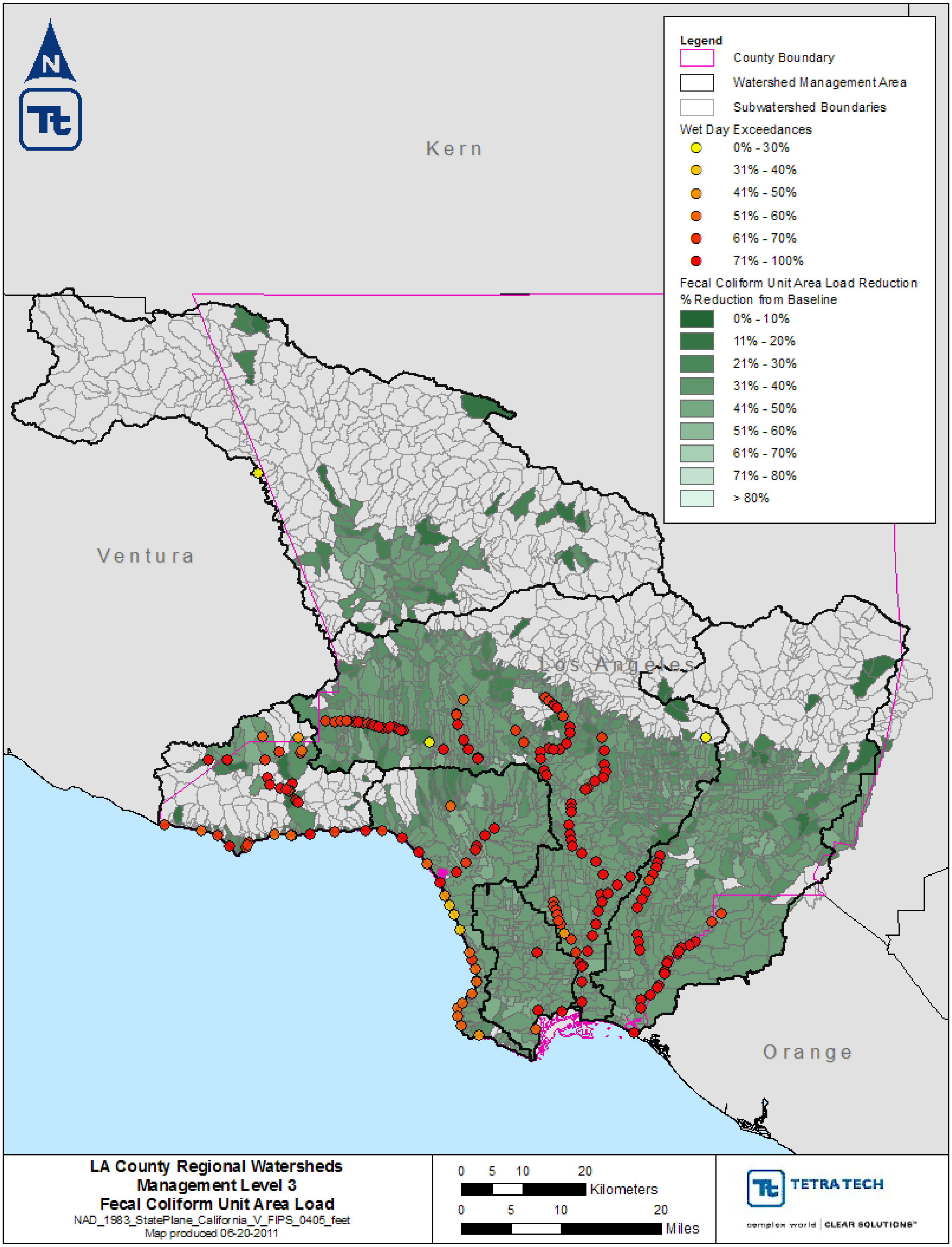

Figure 48. Management Level III fecal coliform unit area load reduction (% from baseline).

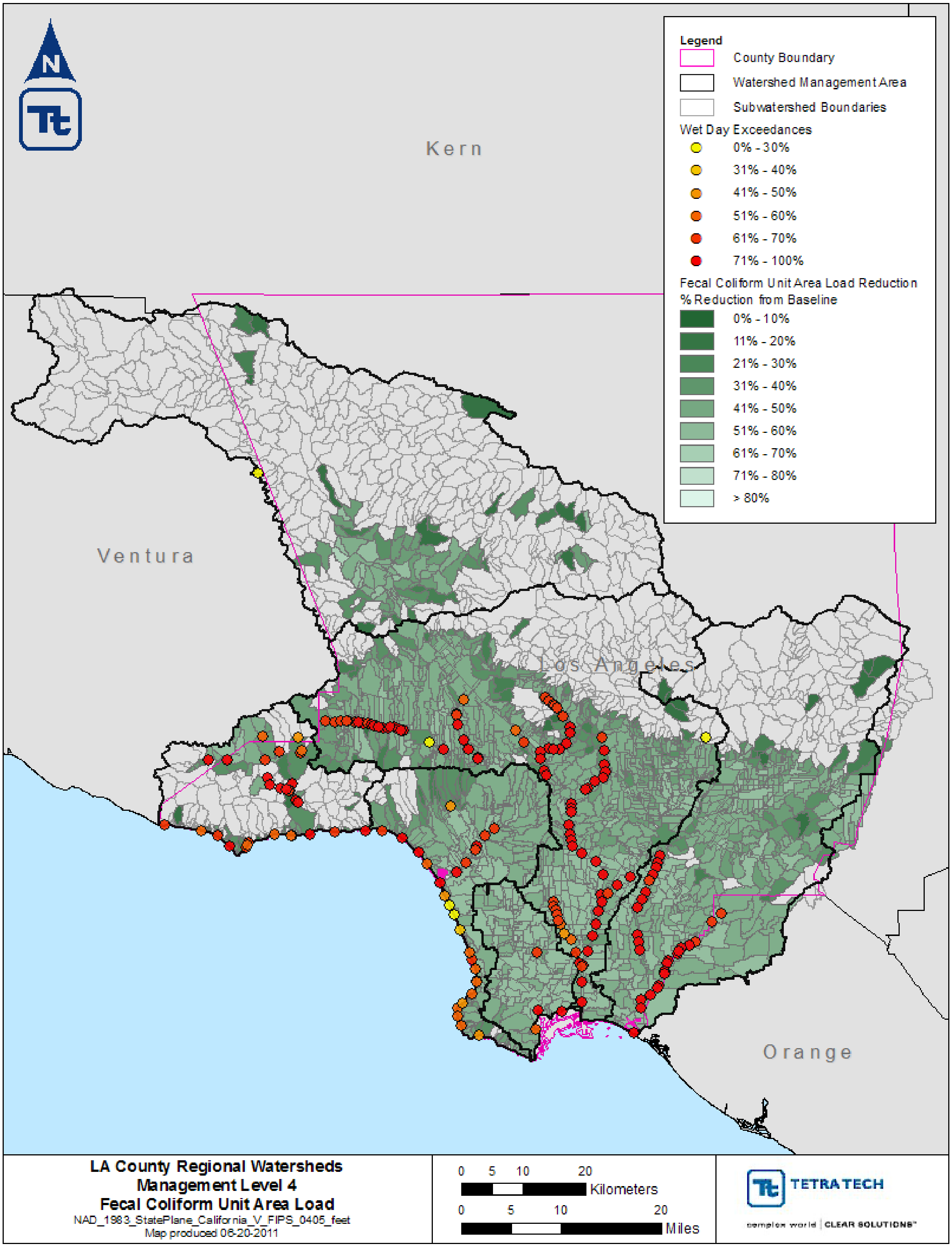

Figure 49. Management Level IV fecal coliform unit area load reduction (% from baseline).

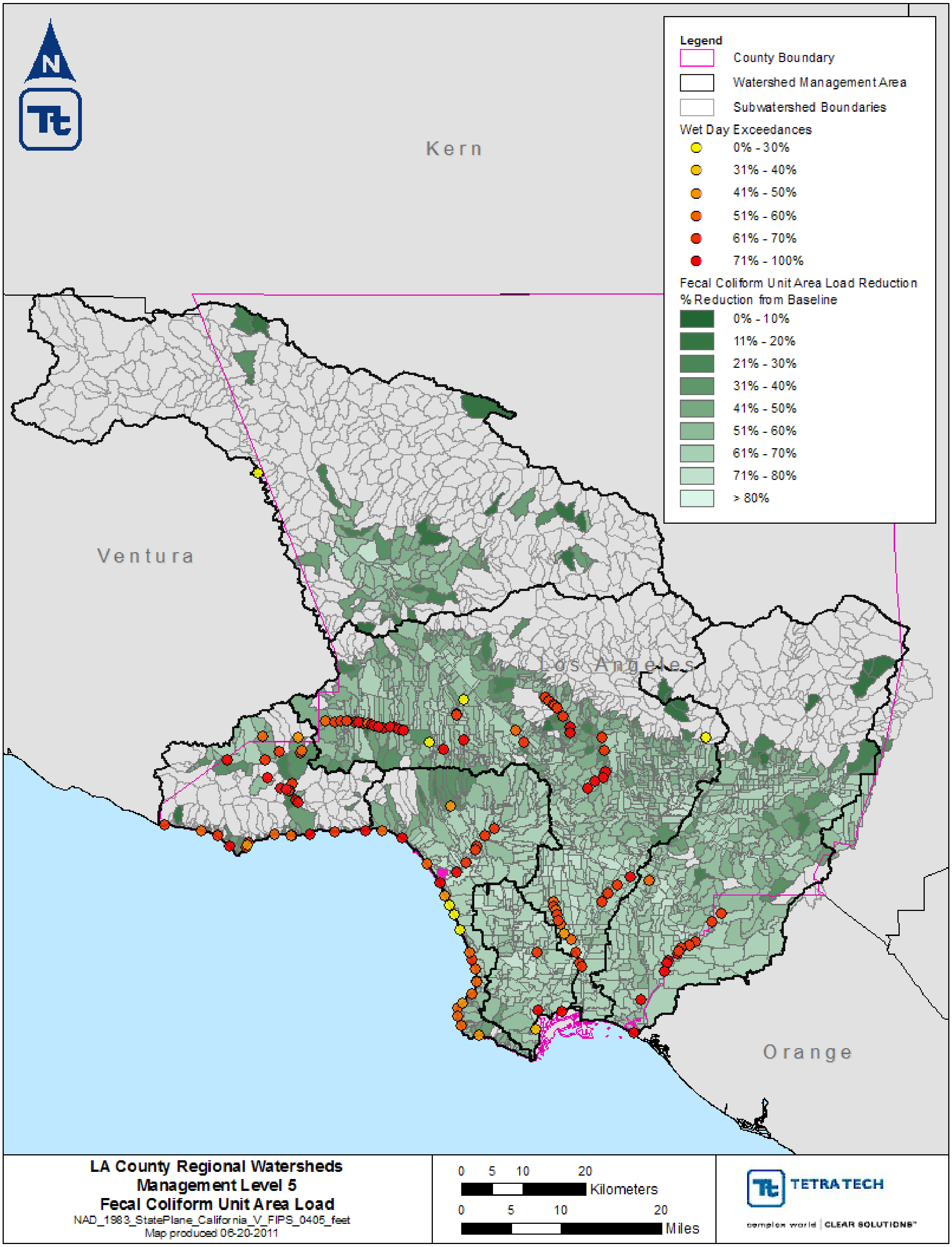

Figure 50. Management Level V fecal coliform unit area load reduction (% from baseline).

5.6 Sediment Reduction Evaluation

As with fecal coliform, sediment concentrations were not evaluated at any in-stream attainment points because no numeric target was available. Since sediment is typically associated with a suite of other pollutants not being modeled, however, there is value to knowing the benefit toward sediment loading associated with managing for the other pollutants. For each subwatershed, an annual average unit area load of sediment (in tons per acre) was calculated by dividing the average annual sediment load by the total subwatershed area. Figure 51 is a map that shows the baseline unit area load for sediment by subwatershed under existing conditions. Figure 52 through Figure 56 are maps that show the unit area load for sediment under Management Levels 1 through 5. Only the loads from urban subwatersheds are shown in these maps to better highlight the benefits associated with the urban Management Levels.

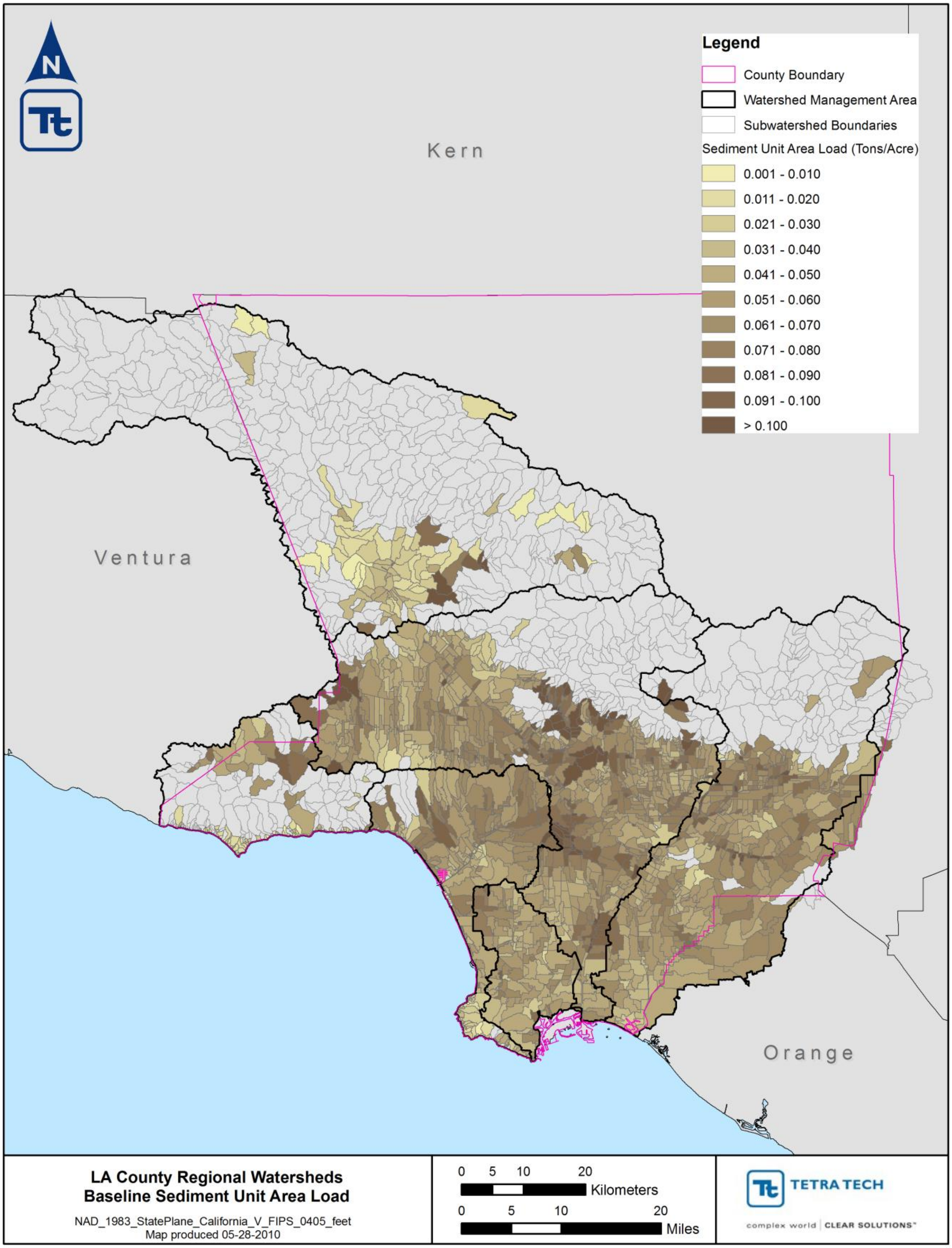

Figure 51. Baseline sediment unit area load by subwatershed.

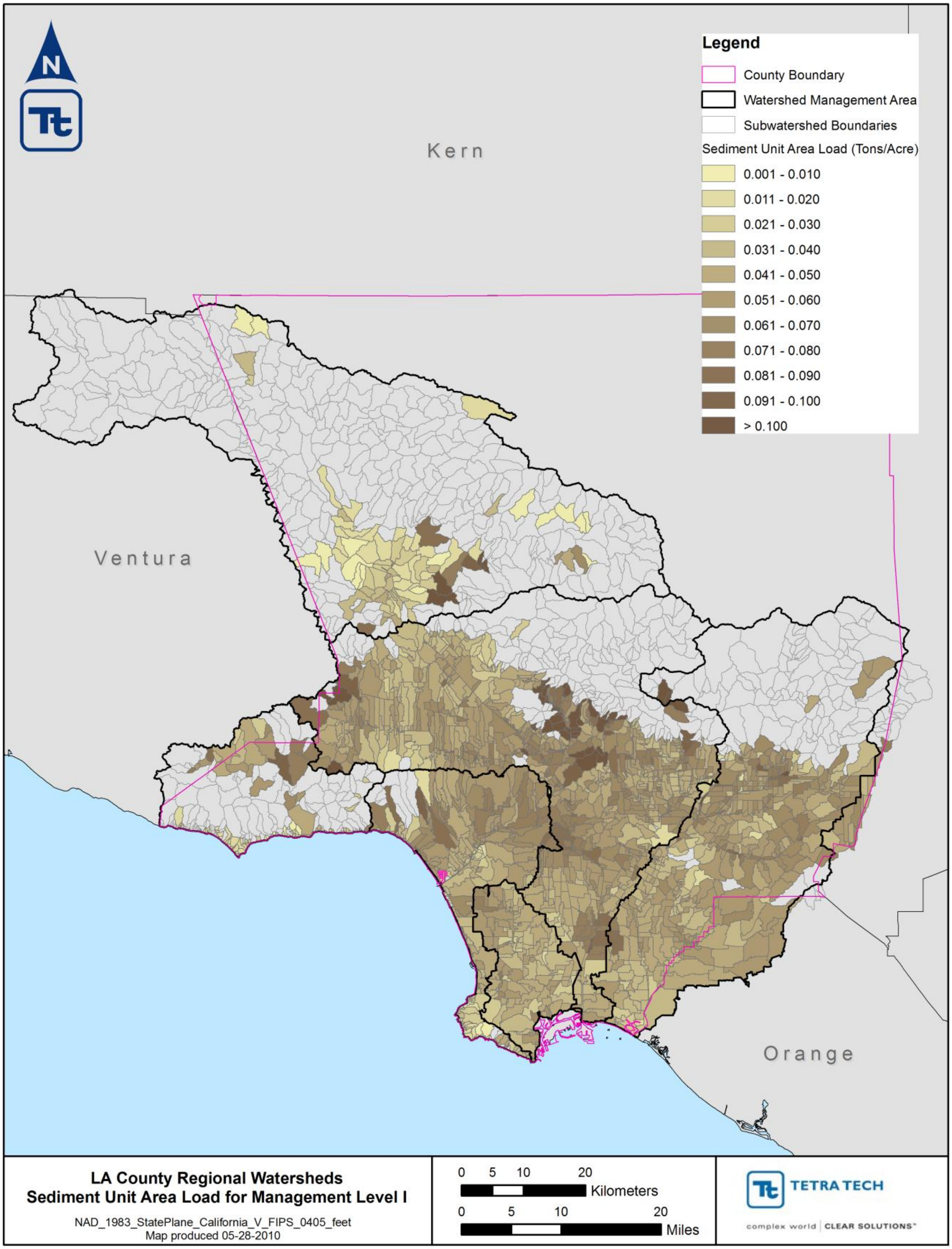

Figure 52. Management Level I sediment unit area load.

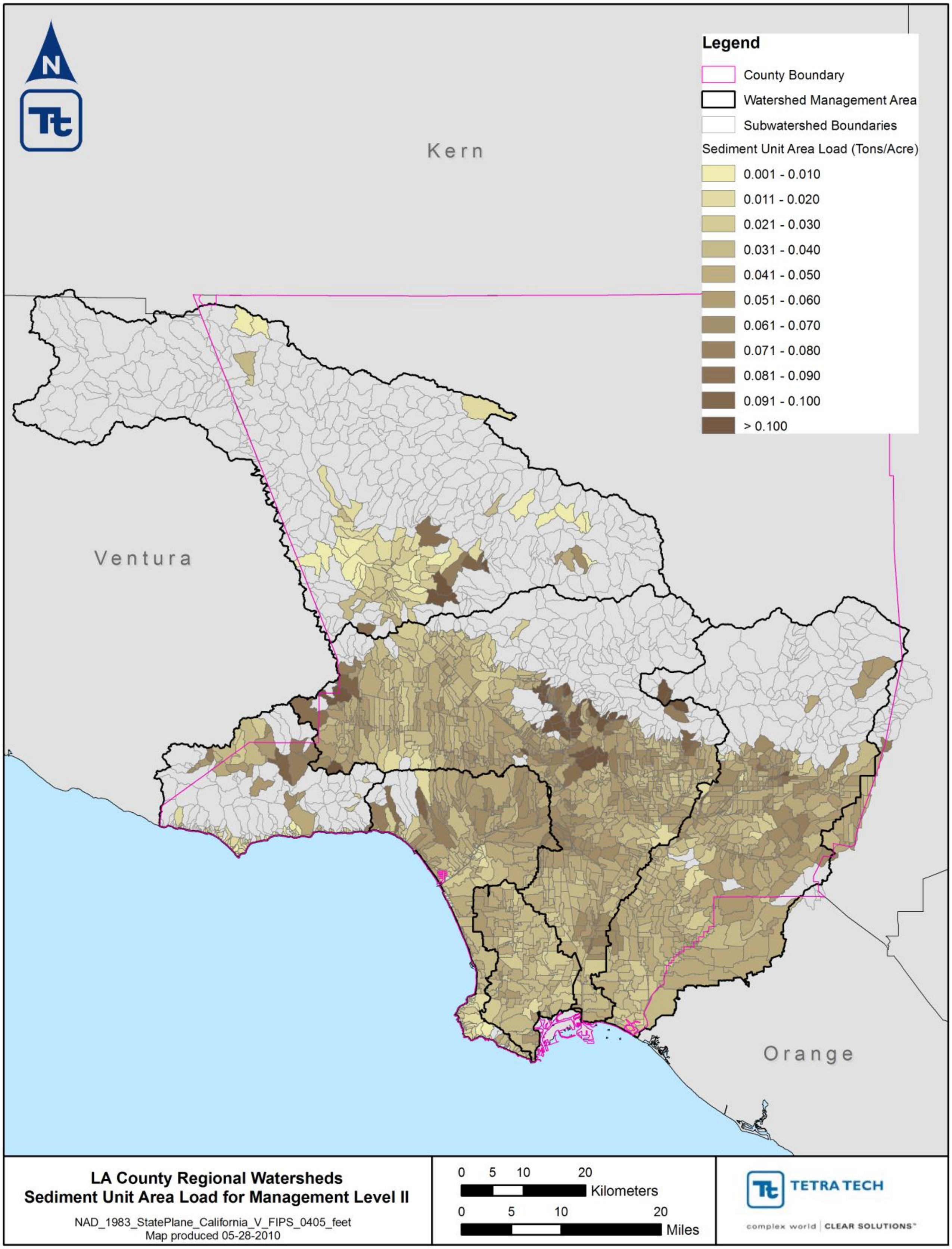

Figure 53. Management Level II sediment unit area load.

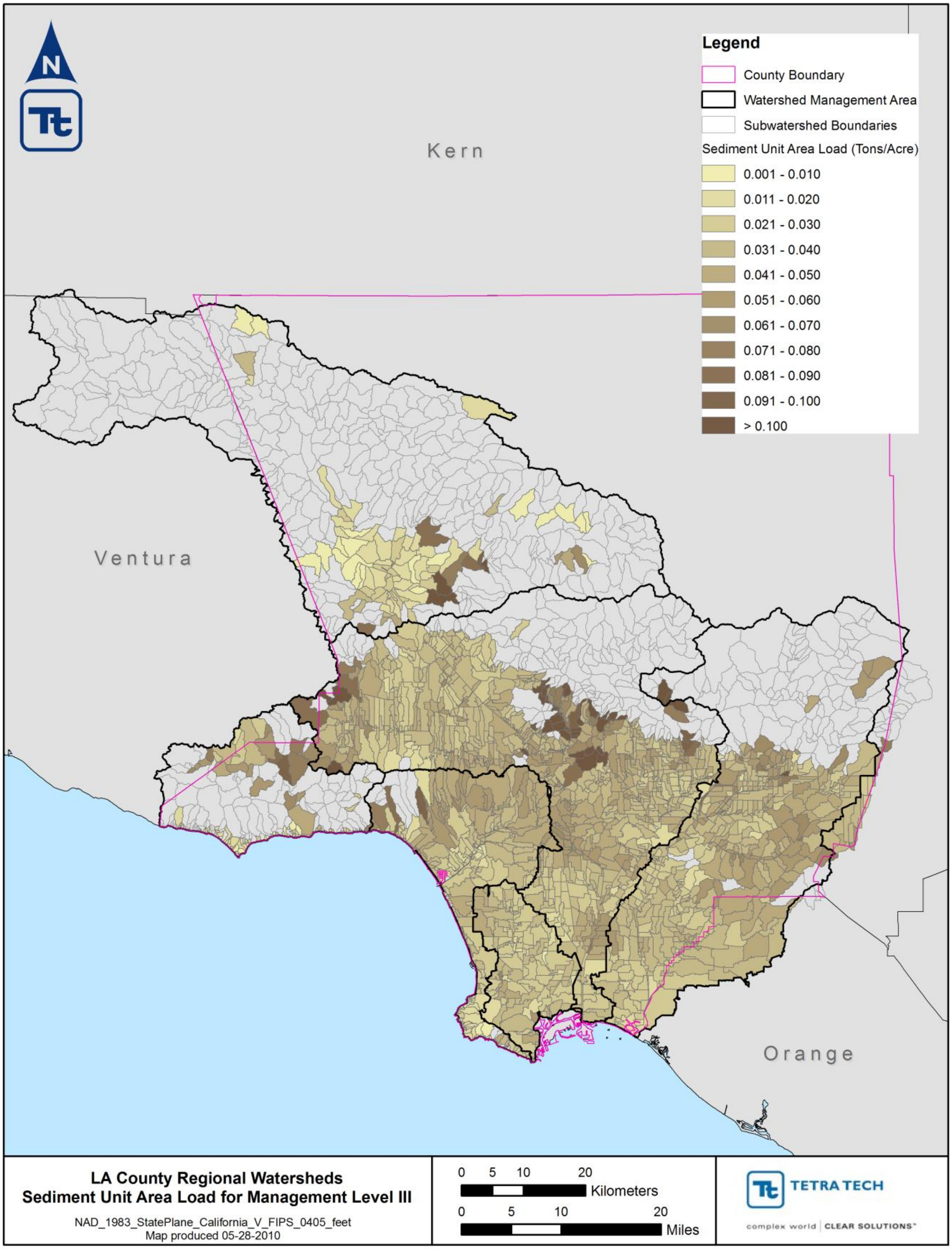

Figure 54. Management Level III sediment unit area load.

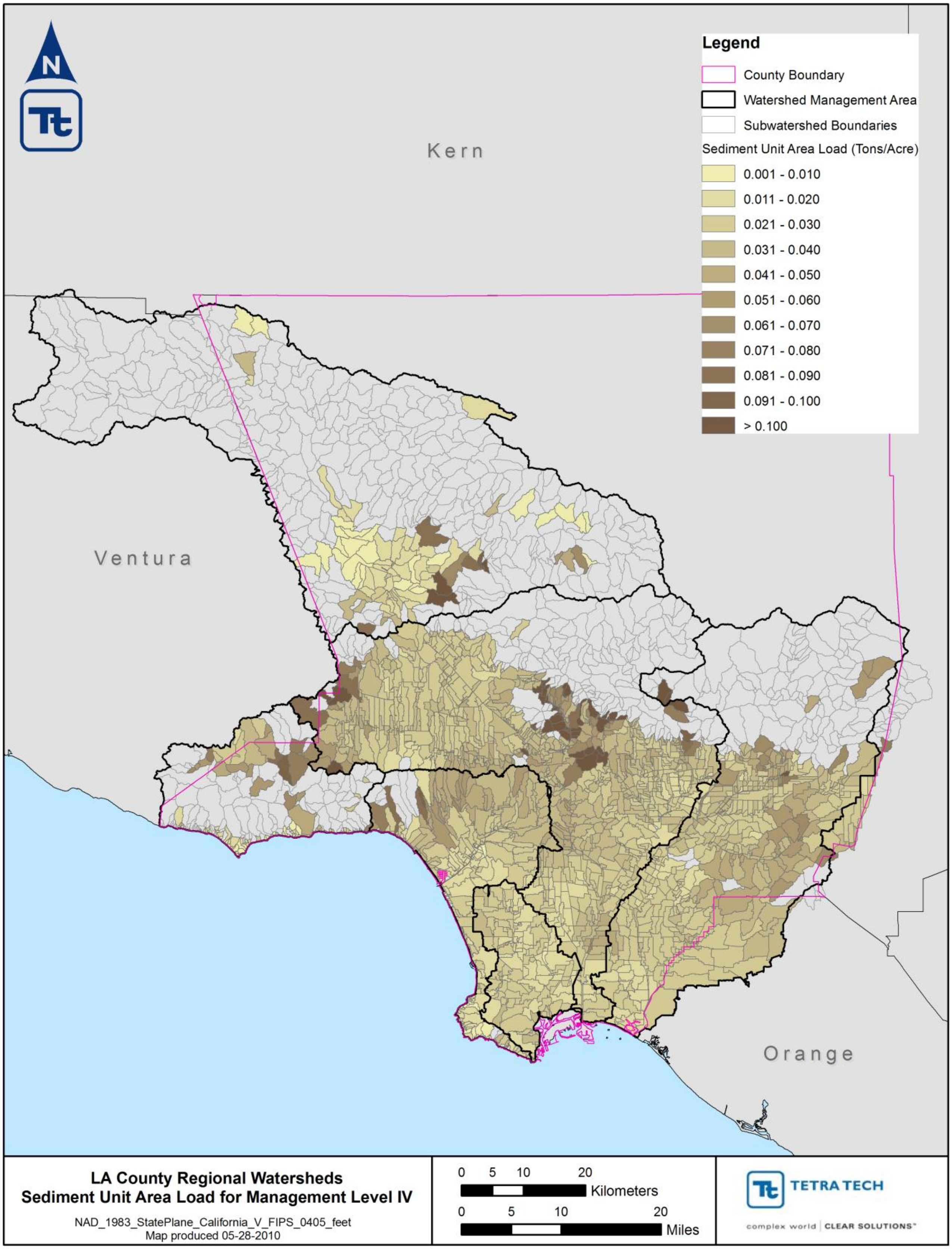

Figure 55. Management Level IV sediment unit area load.

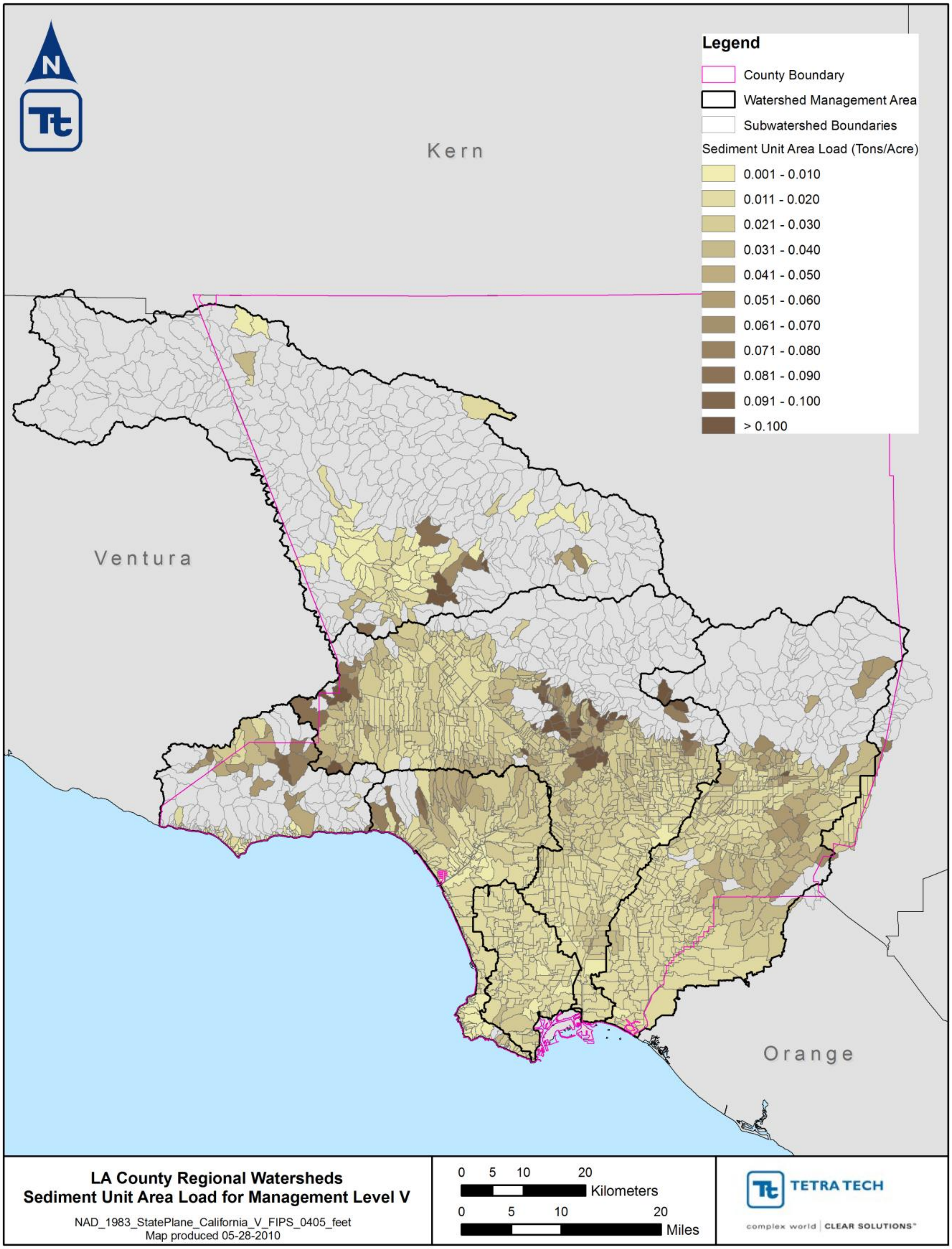

Figure 56. Management Level V sediment unit area load.

5.7 Storm Response Evaluation

As the Management Level increases, both the amount of impervious area treated and the BMP Treatment Capacity increase. The C-50 subwatershed (6057) was selected to demonstrate the responsiveness of selected Management Level treatment capacity to different storms. First, the 10-year precipitation time series for that subwatershed was categorized into storm event intervals using 72 dry hours as the event-interval separation criterion. Second, the BMP configuration associated with each Management Level was used to simulate the storm responses. Third, each storm response for each Management Level (percent reduction relative to baseline) was plotted versus the corresponding rainfall. The “critical storm” for each Management Level was identified as the point on this curve where BMP performance begins to drop precipitously as storm size increases. Figure 57 identifies “critical storms” associated with the C-50 subwatershed at each of the five Management Levels. As expected, higher Management Levels have higher critical storms because of higher treatment capacity.

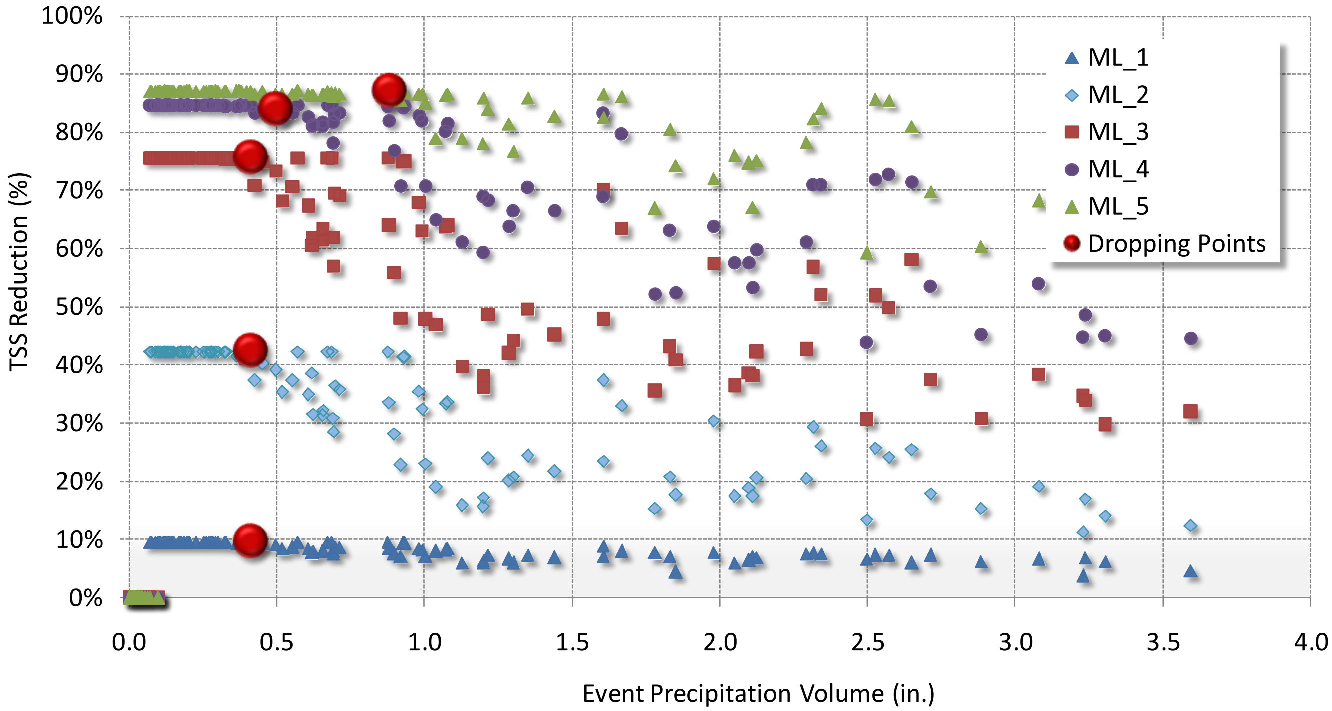

Figure 57. Critical storms at five Management Levels for C-50th representative subwatershed.

To illustrate the effect of Management Levels for a particular event, the critical storm associated with Management Level 4 was selected. Figure 57 also shows the performance associated with the selected critical storm for Management Level 4. For the same storm, BMP performance hydrographs and pollutographs were generated for each Management Level, compared to a baseline hydrograph and pollutograph response. Figure 58 is the rainfall hyetograph associated with this storm. Figure 59, Figure 60, and Figure 61 show the flow hydrographs , TSS load response, and total zinc load response, respectively. From these graphs it clear to see how performance improves with increasing Management Level for a given storm.

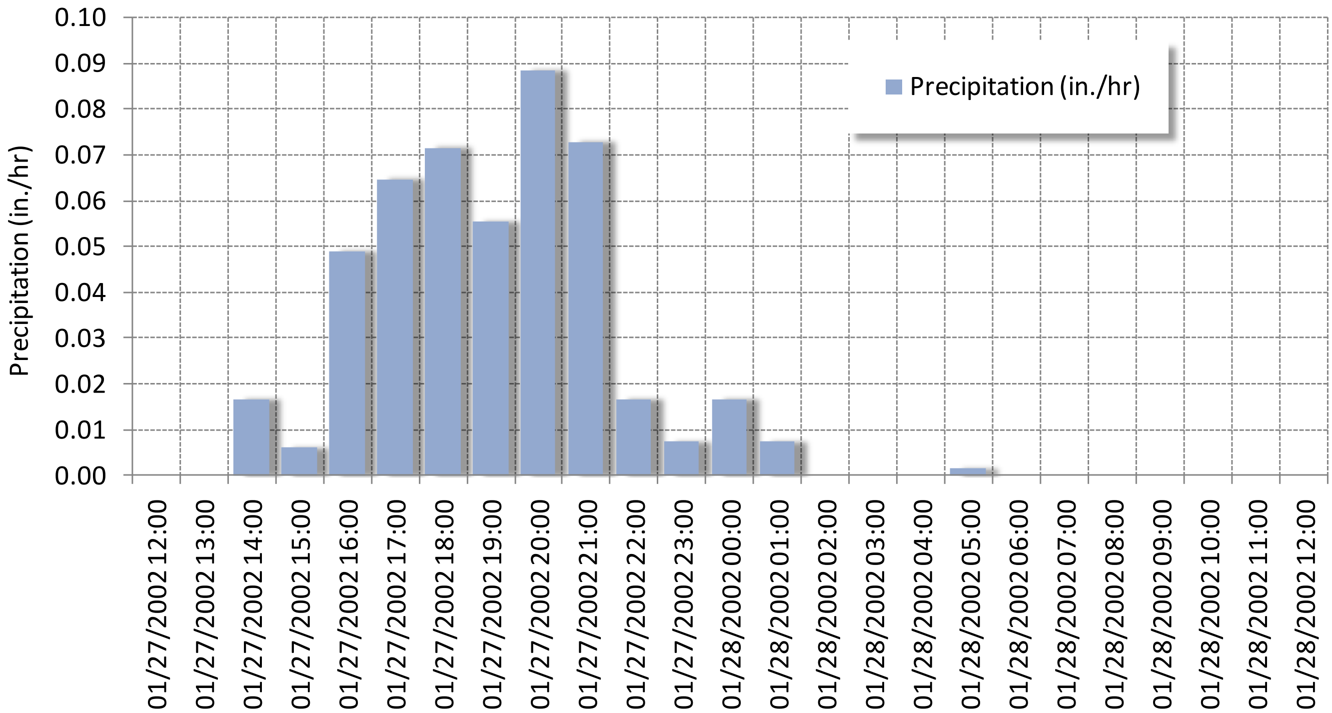

Figure 58. Rainfall hyetograph for the 0.5-inch critical storm for Management Level 4 at subwatershed C-50.

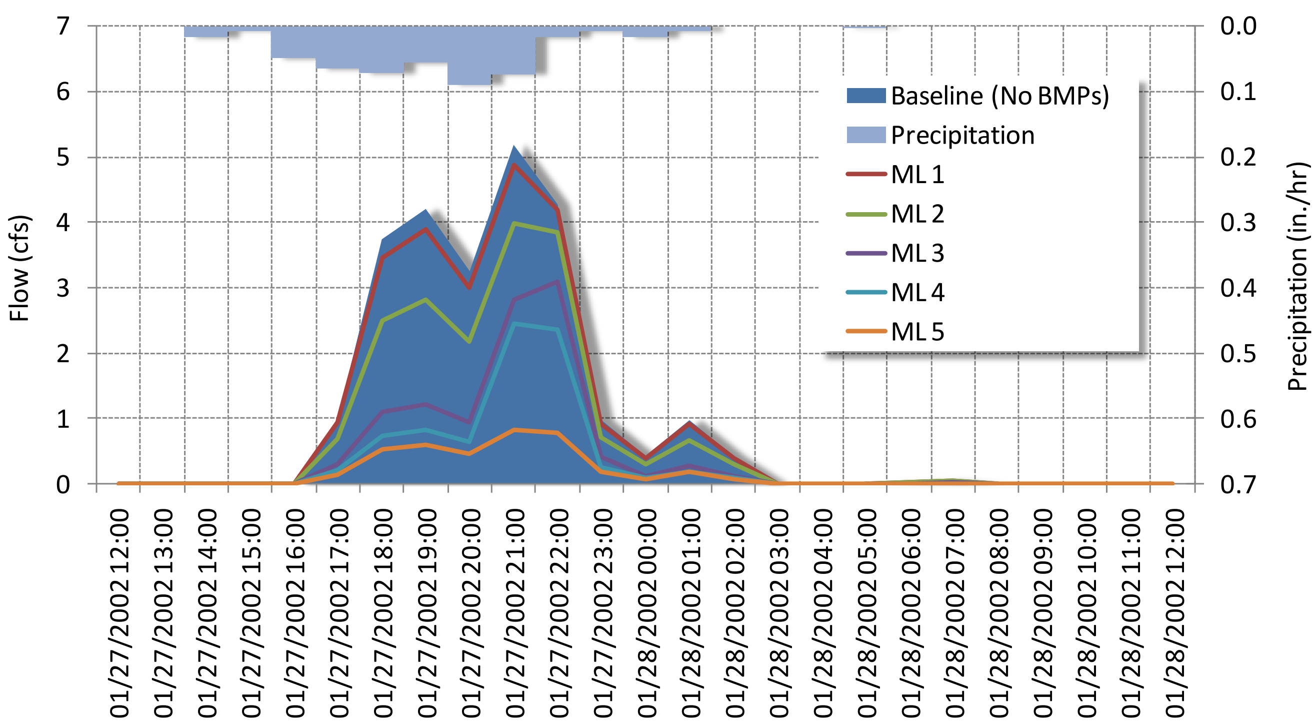

Figure 59. Comparison of flow time series of the 0.5-inch storm at five Management Levels.

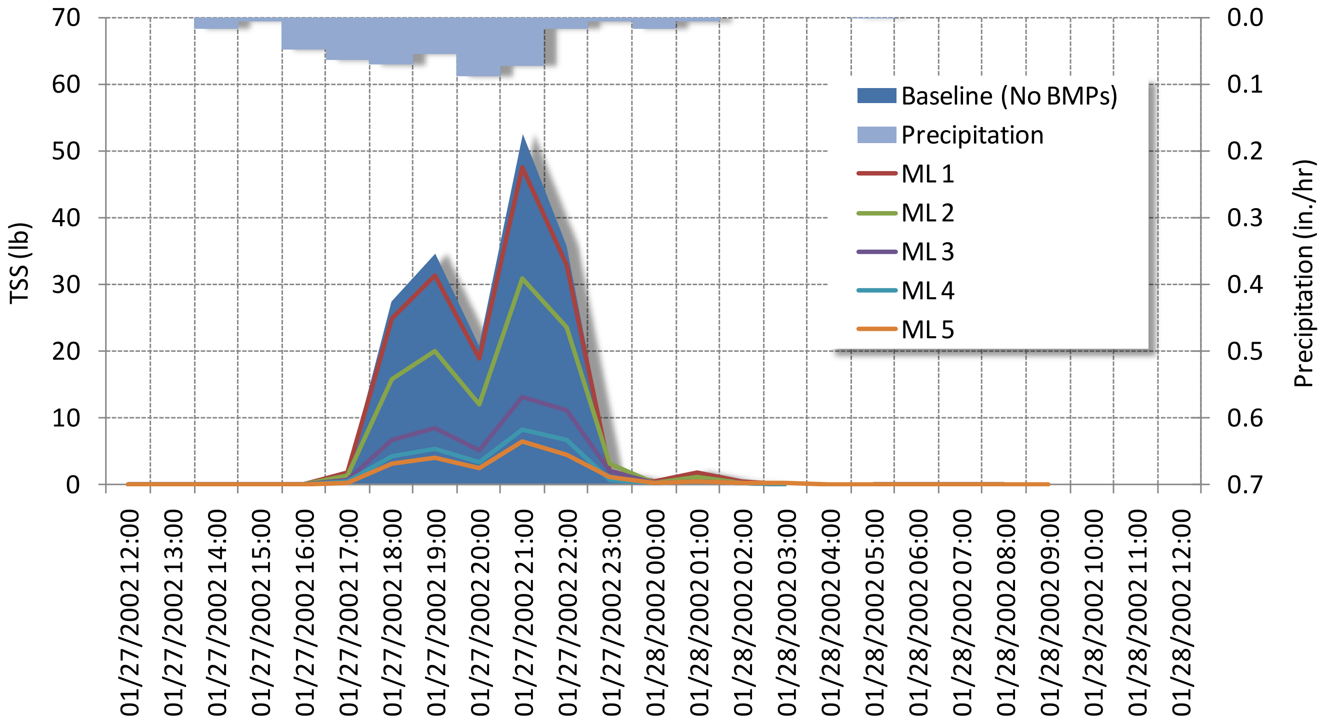

Figure 60. Comparison of TSS loading time series of the 0.5-inch storm at five Management Levels.

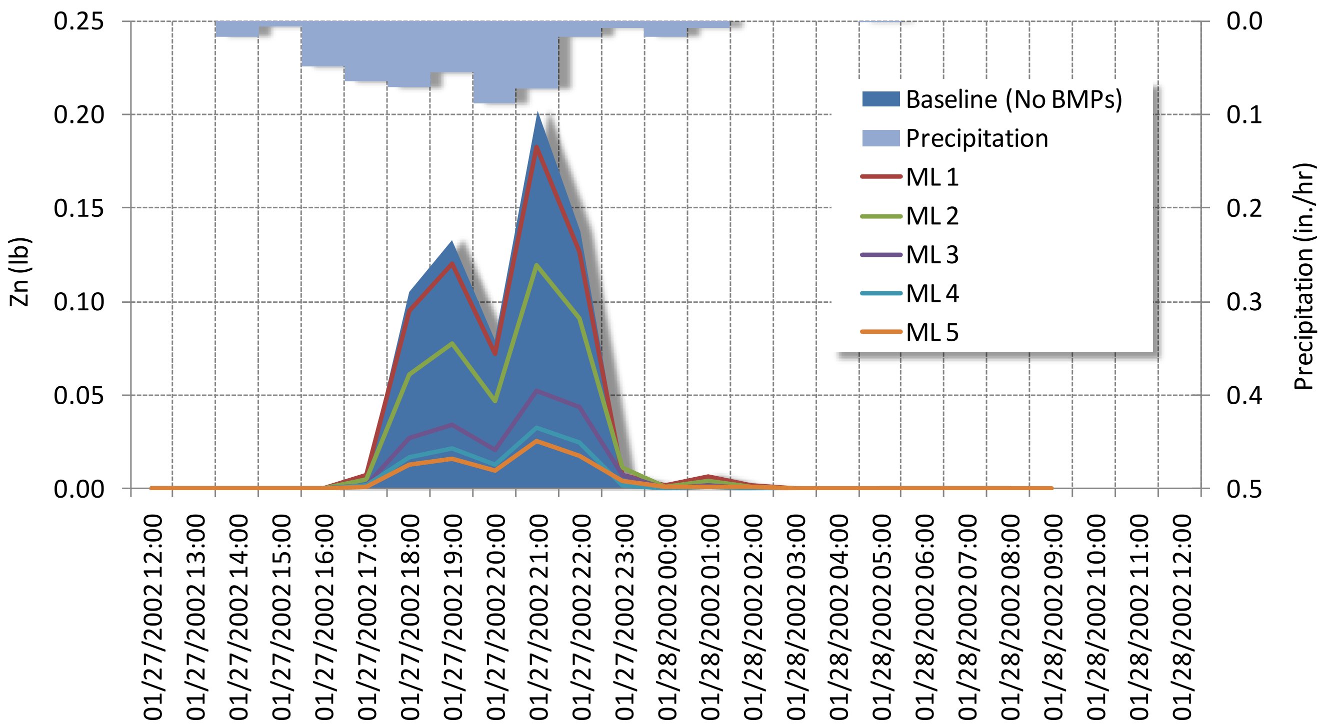

Figure 61. Comparison of zinc loading time series of the 0.5-inch storm at five Management Levels.

6 The Water Quality Design Storm

This analysis began with the selection of 148 rainfall gages that well represent the precipitation patterns in the County. Precipitation records for these selected stations include 21 years of rainfall data covering calendar years 1986 through 2006. Model results for 20 water years (October 1,1986 through September 30, 2006) were considered during the analysis. As previously described, Thiessen polygons derived with these stations were used to assign precipitation data from rain gages to subwatersheds on the basis of the gage with the highest percent coverage of the polygon per subwatershed.

Storm duration was established by sorting precipitation data at each rain gage into wet intervals. For this analysis a wet/storm interval was defined as a time duration of precipitation bounded on either end by 72 dry hours. The maximum 24-hour rainfall depth was then calculated for each storm interval. A percentile analysis was performed on each precipitation gage, using the maximum 24-hour rainfall depth from each storm interval. The results of this percentile analysis were associated with subwatersheds using the same Thiessen polygon assignments referenced above. This section presents two options for the water quality design storm.

6.1 Distributed with Centralized Inflection Point

The first option presented below is the scenario that identified the most cost-effective point in the search space that considered both distributed and centralized BMPs. This point occurred for the scenario with uniform application of Management Level 3 for Degree of Practice III. That particular inflection point provided the highest, most cost-effective achievable Degree of Practice (90 percent attainment); maximized the use of distributed BMPs (with uniform application of Management Level 3); and minimized reliance on the relatively more costly centralized BMPs. (Centralized BMPs represent less than 10 percent of the total attainment cost.) Treatment depths under consideration for this scenario were set at Management Level III for most subwatersheds. Specific subwatersheds upstream of attainment points not achieving 90 percent TMDL attainment were assigned Management Level IV and V to ensure TMDL attainment. This was done to uniformly distribute the capacity requirements associated with centralized BMPs. These treatment depths were first translated to an equivalent percentile rainfall depth for each subwatershed. Table 9 summarizes the inter-quartile statistical analysis of the relationship between treatment depth as a percentile of rainfall depth by Management Category. Subwatersheds with less than 1 acre of impervious cover were excluded from this tabulation exercise to minimize bias and skew in the results.

Table 9. Summary statistics of treatment depth equivalent percentile rainfall depths.

Impervious Cover	Management Category	Minimum	25th Percentile	Median	75th Percentile	Maximum
Urban	A	75%	87%	91%	93%	99%
	B	68%	88%	91%	94%	100%
	C	79%	89%	92%	94%	99%
	D	65%	87%	90%	93%	100%
	E	75%	87%	90%	93%	100%
Non-Urban	F	75%	86%	91%	93%	98%
	G	87%	88%	89%	89%	90%
	H	6%	79%	86%	90%	100%
	I	1%	81%	83%	86%	95%

Strong trends are apparent in the inter-quartile range when comparing both Urban and Non-Urban Management Categories. Percentile storm size for the Urban Management Categories shows a tight range between the 25th and

75th percentile values. Median and interquartile values are relatively stable tend to be around the 90th percentile storm size for all urban Management Categories.

Percentile storm size values for the Non-Urban Management Categories show more variation. This is reflective of many subwatersheds categorized as Non-Urban currently requiring no treatment based on the site-scale modeling effort that defined Management Levels I through V. The median values at the zero-percentile reinforce this trend that most non-urban subwatersheds currently require no treatment. Statistical summaries of percentile rainfall depth are presented as box-and-whisker plots for urban Management Categories A through E in Figure 62.

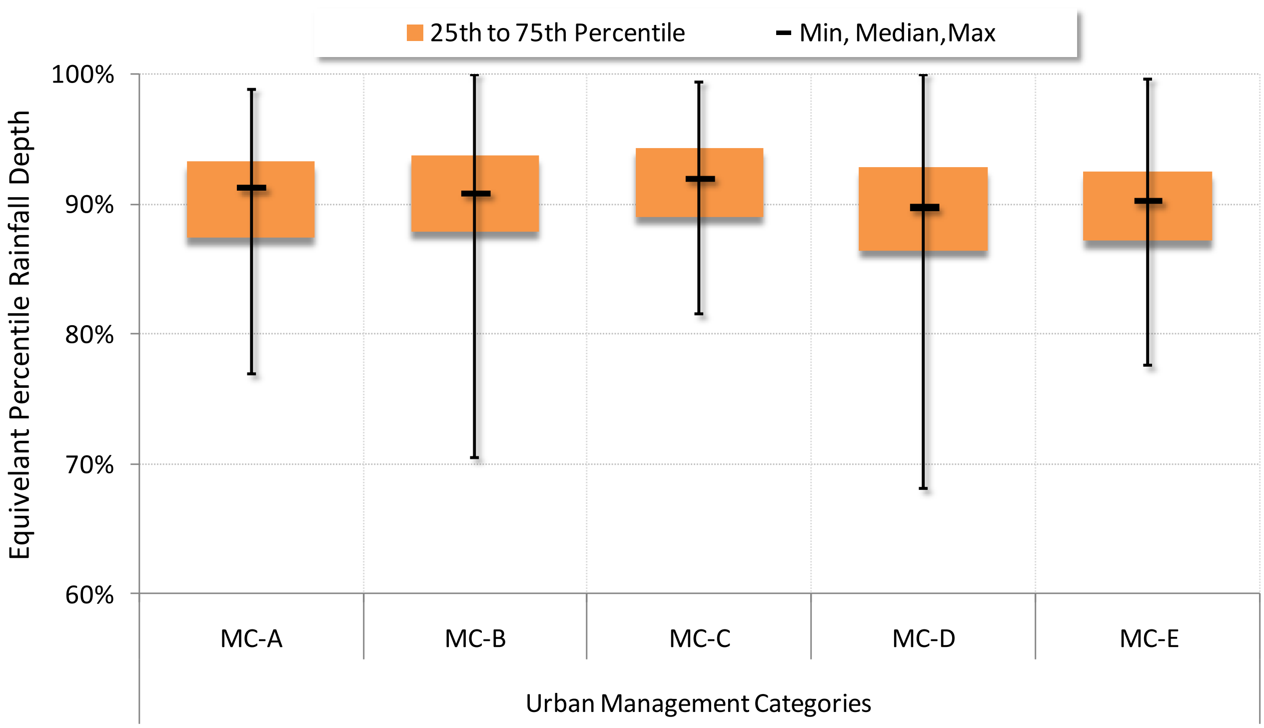

Figure 62. Treatment depth represented as an equivalent percentile storm size by Management Category.

It is important to note that a uniform percentile storm sizing criterion for distributed and centralized BMPs does not guarantee TMDL attainment. The Degree of Practice concept inherently accounts for allowable exceedance in its implementation. Nonetheless, this analysis provides some interesting insights into how the sizing criteria and Degree of Practice relate. Recall that the treatment depths used for this analysis were based on achieving 90 percent TMDL attainment. This analysis suggests that a protective water quality design storm that also achieves 90 percent TMDL attainment is around the 90th percentile storm size, based on the median values of equivalent percentile rainfall depth among the urban Management Categories, as shown in Figure 62. This scenario, however, is heavily dependent on distributed BMPs on private land.

6.2 Centralized Only Inflection Point

The centralized BMP only scenario has some practical application because centralized BMPs are facilities that would be constructed and maintained by public agencies on land acquired by public agencies. For this reason, it would be easier to institute procedures for and ensure proper operation and maintenance. In comparison, distributed BMPs represent a cost-effective alternative, but they rely on private property owners to take responsibility for proper operation and maintenance. Section 5.2 showed the attainment cost for centralized BMPs under the baseline modeled condition for each Degree of Practice and determined that the inflection point associated with an allowable marginal cost threshold of $0.5 billion was at Degree of Practice II, or 85 percent attainment. Because land acquisition is the largest capital expenditure associated with centralized BMPs, they are far more expensive than distributed BMPs, which do not require land acquisition. For this reason, the inflection point above which marginal costs become prohibitive for practical implementation tend to be at a lower Degree of Practice than the scenarios that incorporate distributed BMPs.

Because required treatment depths for 90 percent attainment for the distributed-with-centralized scenario's inflection point was proportional to the 90th percentile rainfall depth, it was hypothesized that assuming treatment capacity per subwatershed at the 85th percentile rainfall depth might also yield 85 percent attainment (Degree of Practice II). To test this hypothesis, a watershed model scenario was constructed to apply estimated load reductions associated with capturing and treating runoff from the 85th percentile rainfall event in every subwatershed.

After reviewing the model results from this scenario run, only one attainment point was not achieving the 85 percent goal when runoff generating the 85th percentile rainfall depth was captured and treated by centralized BMPs. It has a relatively small drainage area (0.9 percent of the total modeled area). For this area, increasing the treatment depth to the 90th percentile rainfall depth allowed for 85 percent attainment. Because 85 percent attainment of water quality standards is achievable by capturing and treating runoff generated by the 85th percentile rainfall event in 99.1 percent of the study area, it is reasonable to deduce that treating the 85th percentile wet-weather runoff and pollutant load from impervious areas will result in 85 percent attainment.

6.3 Spatial Analysis and Presentation of Design Storm Results

The following maps highlight the spatial distribution of the analysis described above. Figure 63 presents the spatial distribution of the percentile storm size analysis from the 90 percent attainment inflection point (described and presented in Table 9 and Figure 62). The model-predicted treatment capacity was translated into percentile storm size values for each subwatershed and plotted as an isohyetal map. Deeper blue values indicated treatment depth correlated with higher percentile storm sizes. Because a relationship was established between 90 percent attainment and the 90th percentile rainfall depth, Figure 64 was created to show the 90th percentile 24-hour isohyets using the 148 rainfall gages driving the watershed model. Similarly, Figure 65 was created to show the 85th percentile 24-hour isohyets resulting from the set of rainfall gages. Finally, as a means of comparison, Figure 66 is a map comparing the 90 percent attainment treatment depths with the 85th percentile isohyetal map. The orange-to-red scale shows subwatersheds where the treatment depth increases, while the green scale shows subwatersheds where the treatment depth decreases. Increased trends in treatment depth are concentrated in urban Management Categories. Decreased trends in treatment depth are concentrated in undeveloped, non-urban management categories. Correlated spatial patterns emerge when comparing Figure 63 with Figure 66. The transportation routes have been included to show how required treatment depth is expressed as a function of spatially variable physiographic characteristics such as land use and weather. Including transportation routes provides a development context for viewing the data and understanding the spatial correlation of the model-predicted treatment depth requirements. For practical purposes, the water quality design storm should nonetheless be expressed as a percentile of rainfall depth for scalability, transferability, and adoption for design purposes.

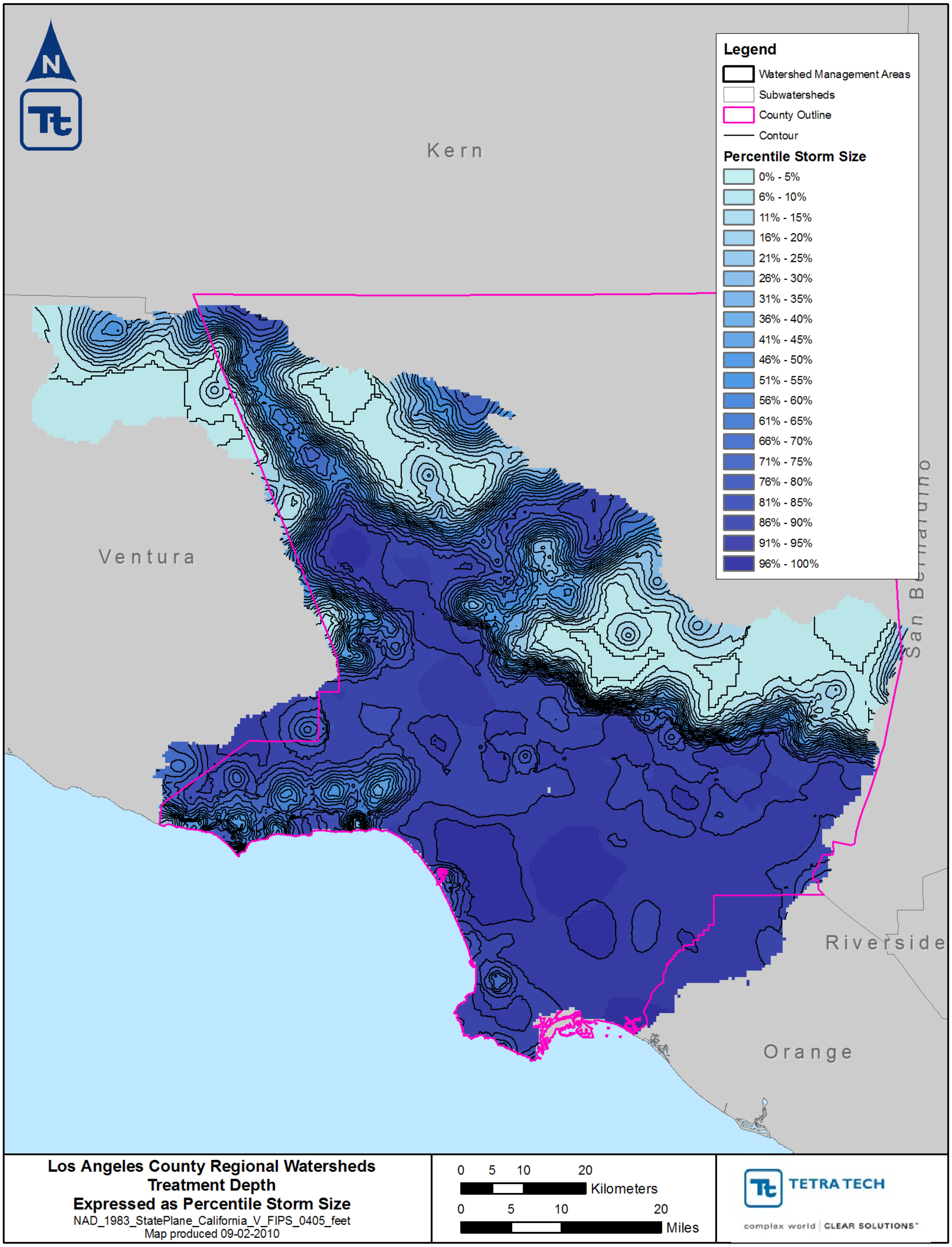

Figure 63. Spatial distribution of 90% attainment treatment depth expressed as percentile storm size.

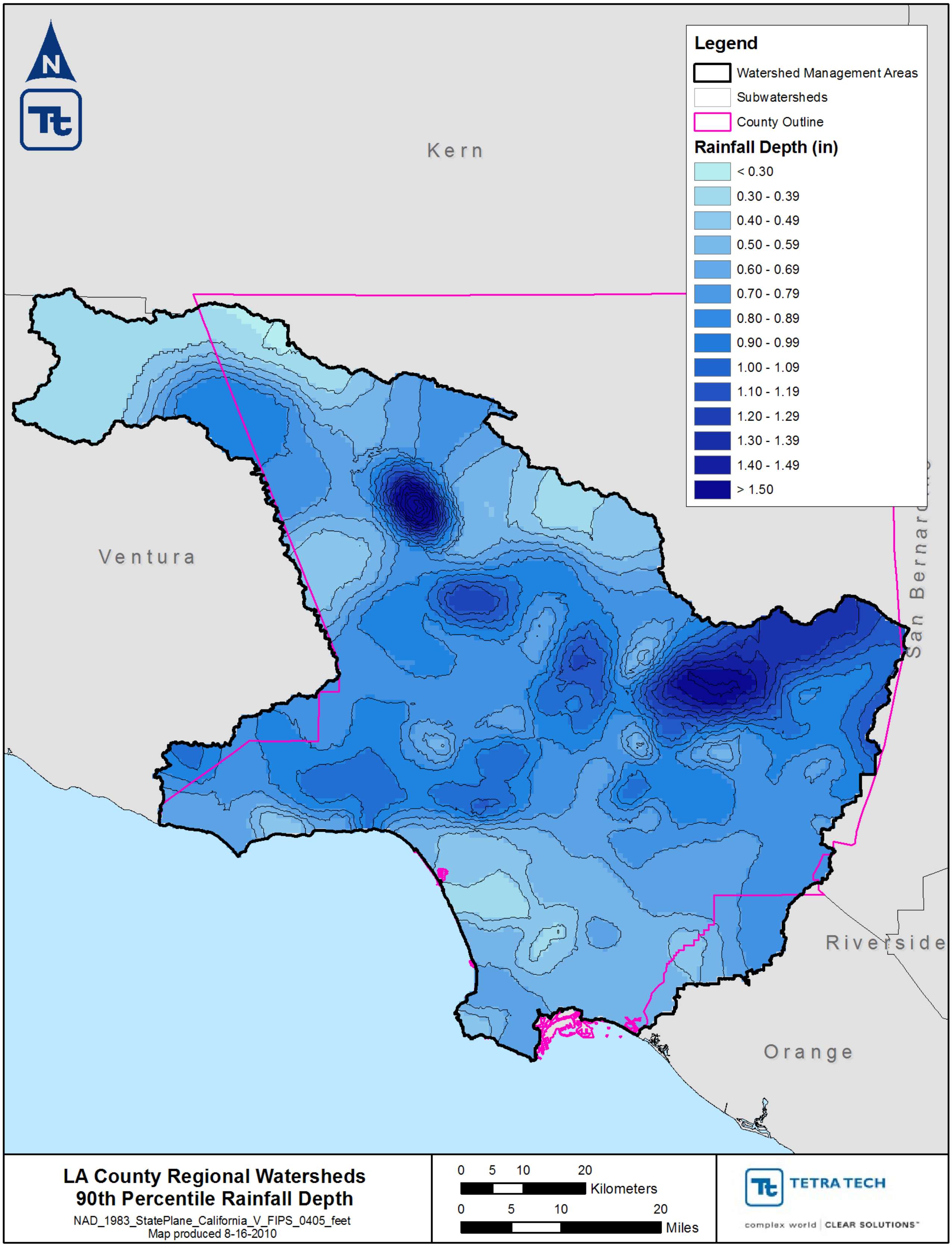

Figure 64. Ninetieth percentile rainfall isohyetal map.

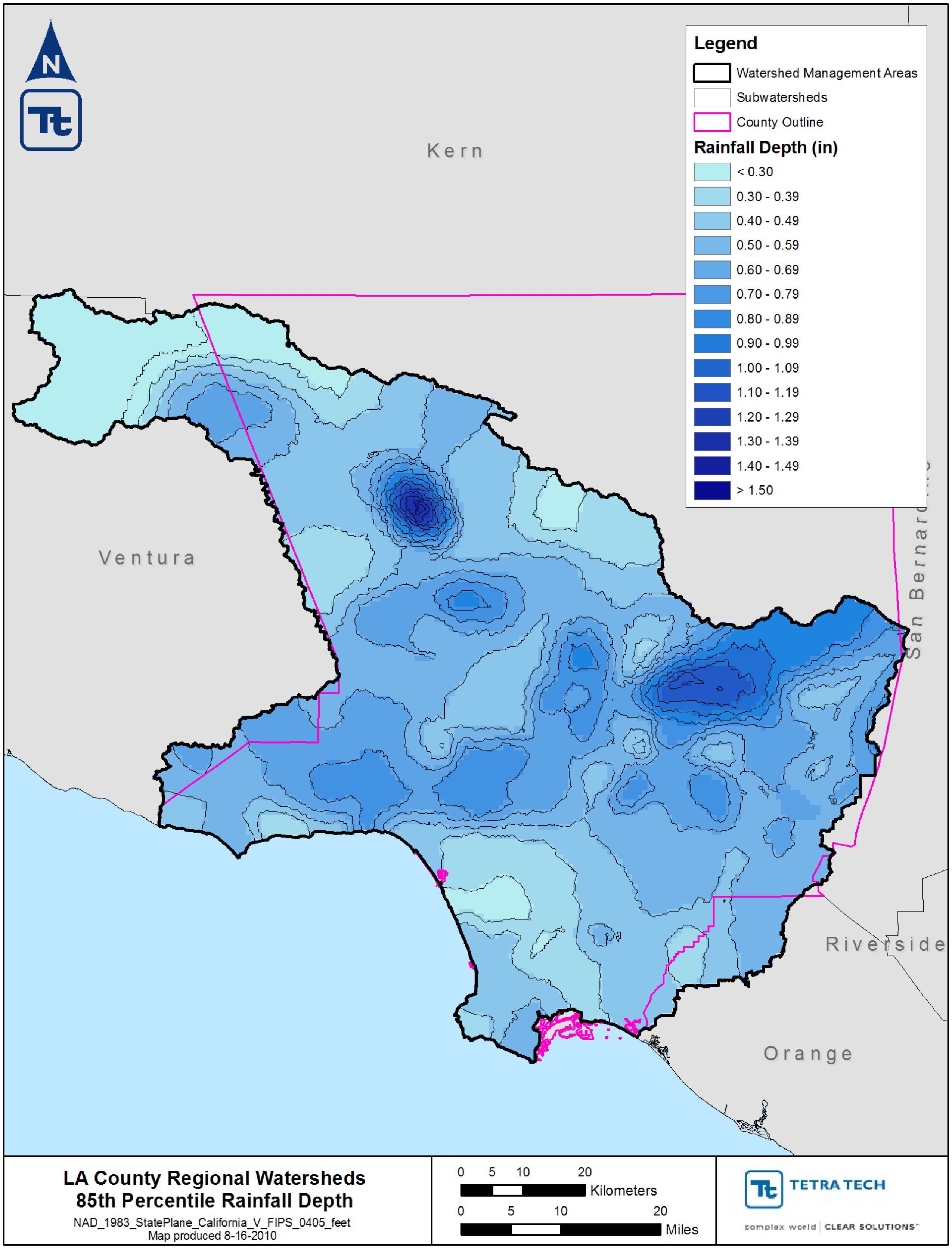

Figure 65. Eighty-fifth percentile rainfall isohyetal map.

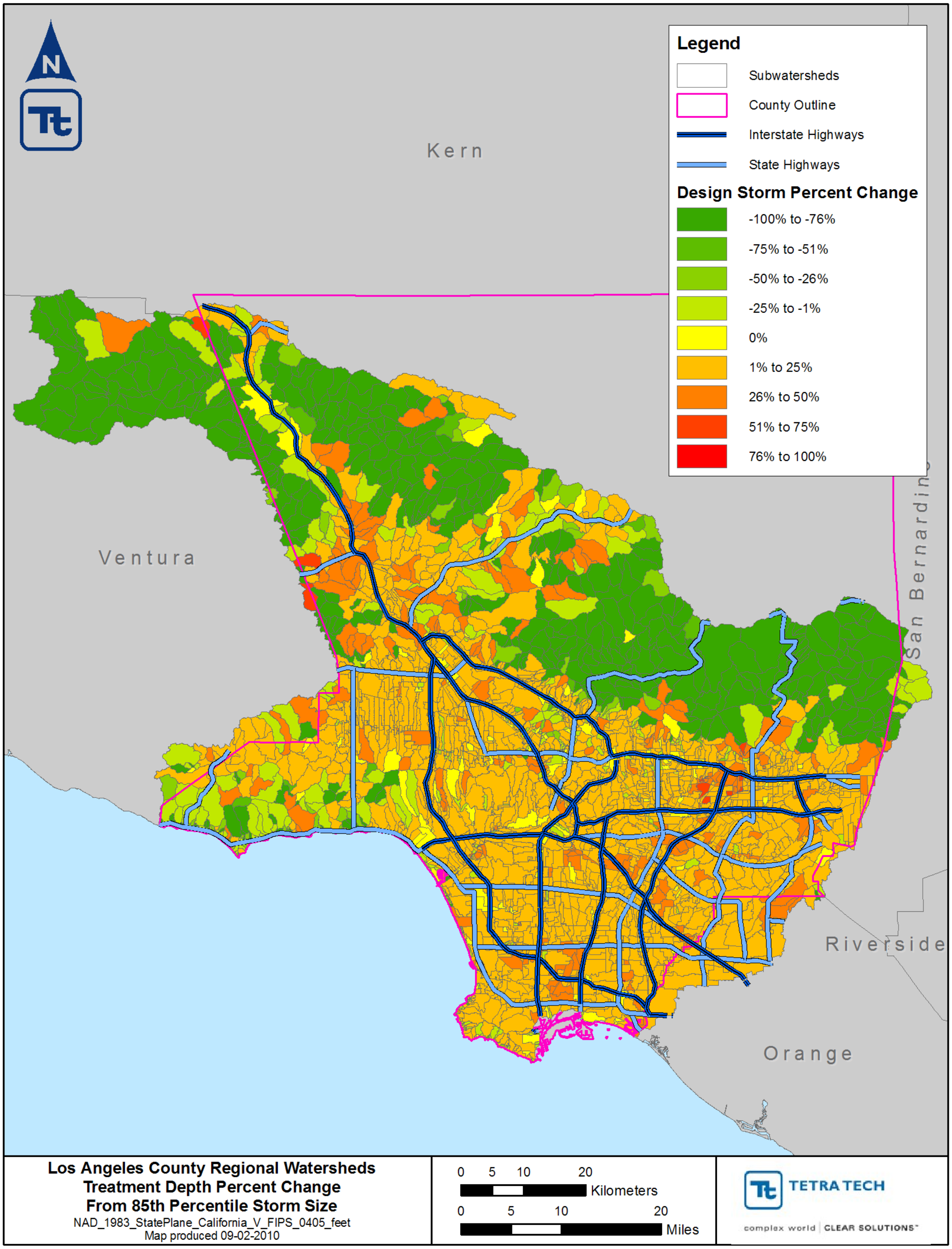

Figure 66. Treatment depth percent change with overlay of major transportation routes.

7 Summary and Conclusions

Identification of a water quality design storm can assist in: (1) Identifying the threshold storm size for treatment that is economically reasonable for pollutant reduction, leading to the concept of the maximum extent practicable (MEP) for structural BMP implementation; and (2) Determining BMP sizing recommendations for meeting water quality standards or TMDL attainment. Results from this analysis have proposed threshold storm sizes that can be treated for best pollutant reduction benefits, while considering economic impacts. Integrated cost-benefit analyses in a watershed context can potentially lead to identification of MEP targets, and provide insights for BMP implementation to achieve instream water quality standards.

This report describes a methodology for identifying a water quality design storm criterion that is based on both (1) the required treatment (or BMP storage) capacity at the subwatershed scale and (2) in-stream attainment with known water quality standards. BMP cost-benefit optimization is used as a tool to navigate through the search space of BMP opportunities in order to determine the optimal distribution of BMP treatment capacity (Management Levels) within each subwatershed for evaluating TMDL attainment at the large watershed scale. This approach involves continuous simulation to characterize long-term BMP effectiveness under a range of conditions, which provides insightful information to inform the overall decision-making process. A number of concepts and terms have been defined and applied in the context of this discussion. Each term plays a key role in establishing the concepts associated with defining a water quality design storm. They are summarized below.

Management Categories and Levels. Realizing the complexity and variability of watershed characteristics, the first step was to evaluate and identify key physiographic characteristics that most influence the selection and placement of BMPs associated with watershed characteristics. Management Categories provided a way to organize the subwatersheds into groups according to factors such as impervious cover and density, slope, and road density. Five urban Management Categories were identified. For each Management Category, three representative subwatersheds were selected, covering a range of land use distribution and precipitation patterns. Based on these selected representative subwatersheds, Management Levels were derived using cost-benefit optimization. Management Levels were defined as specific intervals along a cost-effectiveness curve that was derived using optimization for a given subwatershed. They represent treatment using distributed BMP practices only. Increasing Management Levels represent optimal BMP treatment capacity (impervious area and runoff depth treated) associated with increasing treatment levels, where the maximum (Level V) represents a maximum feasible level of treatment for a given subwatershed. Levels I–IV represent 20 percent through 80 percent of the maximum feasible level of treatment on a cost basis.

Degree of Practice. The TMDL targets are specified as in-stream concentrations. Given the dynamics of the concentration values and the considerable, often unquantifiable uncertainty involved in watershed simulation models, it was important to have a way of measuring sensitivity of the optimization results under standard attainment. Degrees of Practice were used as a means of evaluating the sensitivity of water quality standard attainment intervals and the cost of implementation. Five wet weather exceedance allowances (Degrees of Practice I to V) were defined, where Degree I represented 75 percent attainment (25 percent allowable exceedance), while Level V represented 100 percent attainment (0 percent allowable exceedance). At the watershed scale, the model was formulated to obtain attainment using a combination of distributed BMPs (Management Levels), with supplemental centralized BMPs where distributed BMPs were inadequate to achieve the aspired attainment target associated with a given Degree of Practice.

Watershed-Scale Optimization Analysis. An integral component of this design storm analysis that makes this approach unique is the use of large watershed-scale optimization. Recall that Management Levels have been defined for each subwatershed, with doing nothing as an allowable option for any given subwatershed. The different combinations of Management Levels, including doing nothing, represent the search space of opportunity for watershed-scale optimization analysis. In addition, if attainment to a given Degree of Practice using only distributed BMP Management Levels is found to be infeasible, additional centralized BMP storage is computed on a subwatershed scale until attainment is achieved. To illustrate the watershed-scale search space, five uniform-application Management Level scenarios were modeled to examine attainment at all assessment points. For example, what if Management Level I were applied in every subwatershed for Degree of Practice I? What would TMDL attainment look like, and how much would it cost?

The spatial and temporal results presented in this report reveal some important patterns worth noting:

- For a given Degree of Practice, when increasing Management Level, more non-attaining locations generally become attaining (Figure 38 through Figure 42).
- When increasing the Management Level, total cost of distributed BMP implementation increases in a nonlinear fashion (ranging from $4.08 billion for Level 1 to $44.48 billion for Level 5); however, to achieve attainment at differing Degrees of Practice, centralized BMPs are needed at differing degrees.
- For the same uniform application of Management Level 5 at Degree of Practice V (100 percent wet-weather attainment), *most* of the in-stream points are *not* in attainment (Figure 43); therefore, a much larger number of centralized BMPs are required to achieve attainment.
- Two extreme scenarios of BMP implementation were analyzed to cover a broad range of real world BMP implementation situations: (1) centralized BMPs only and (2) maximum use of distributed BMPs supplemented by centralized BMPs if necessary:
    - If only centralized BMPs are considered for baseline attainment at each Degree of Practice, the most cost-effective point (measured by an allowable marginal cost threshold of $0.5 billion) occurs at Degree of Practice II (85 percent attainment). In terms of a design storm threshold, capturing the 85th percentile rainfall depth using strategically located centralized BMPs results in 85 percent TMDL attainment for 99.1 percent of the entire study area.
    - If distributed BMP use is maximized and centralized BMPs are used only if necessary, the most cost-effective point occurs at Management Level 3 for Degree of Practice III (90 percent attainment). This option minimizes reliance on the relatively more costly centralized BMPs; Centralized BMPs represent less than 10 percent of the total attainment cost. Achieving 90 percent TMDL attainment at Degree of Practice III is achievable by designing distributed BMPs to capture runoff associated with the 90th percentile rainfall depth.
    - Considering the two extreme BMP implementation scenarios analyzed above, it was concluded that the water quality design storm can be at minimum 85th percentile storm event depending on actual implementation scenarios as treating storms beyond 85th percentile storms for attainment of water quality standards will not be cost-effective and may not be practicable. Therefore, 85th percentile storm event is recommended as Water Quality Design Storm.
- If TMDL attainment beyond the levels suggested above is the goal (i.e. 100 percent TMDL attainment), it is more cost-effective to focus nearly exclusively on centralized BMPs (gray infrastructure) and minimize distributed BMPs (LID-type green infrastructure). The analysis also suggests, however, that the distributed BMP implementation opportunity should not be entirely ignored because adopting distributed BMPs at even the lowest adoption level significantly reduces the centralized BMP requirement.

In conclusion, this integrated continuous simulation and optimization BMP design approach provides many advantages over the traditional design storm approach. First, the long-term continuous simulation allows for a robust testing and understanding of BMP effectiveness under a wide range of conditions. Second, using the attainment target as a requirement that drives the BMP sizing ensures that the final result has taken into consideration the need to address existing TMDL objectives. Finally, the use of optimization techniques provides opportunities to identify cost-effective combinations of management strategies that are spatially optimized to ensure the highest likelihood of TMDL attainment at the lowest cost.

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